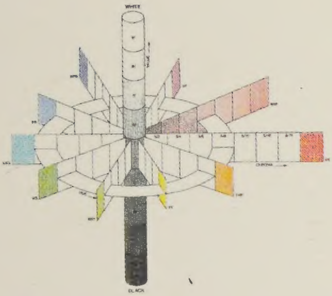
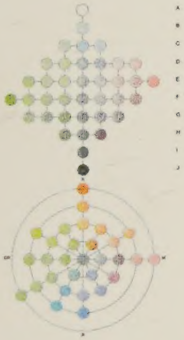
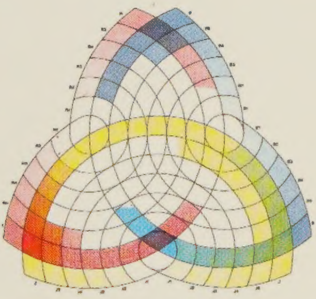
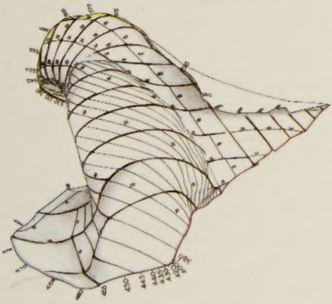
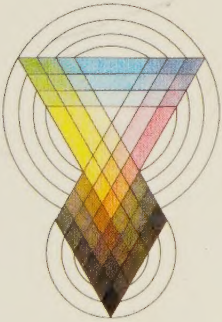
COLOR SYSTEMS











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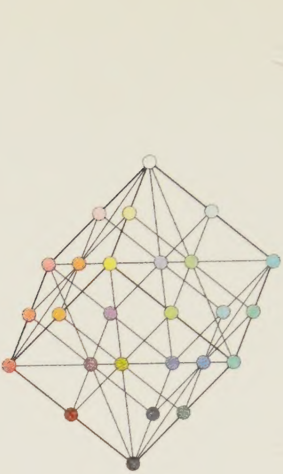

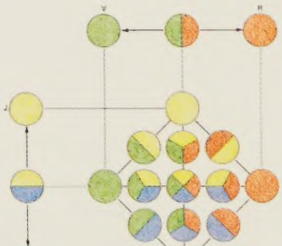

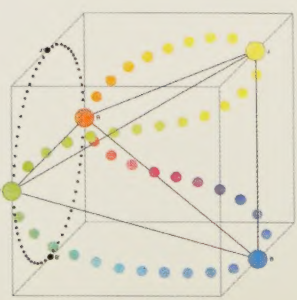

COLOR SYSTEMS

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IN ART AND SCIENCE

GOLDEN
ARTIST COLORS ®

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Editor: Klaus Stromer
Authors: Narciso Silvestrini
Ernst Peter Fischer
Urs Baumann
Klaus Stromer
Translation: Randy Cassada
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PREFACE

Golden Artist Colors, Inc. is proud to be able to make available the first English translation and the second printing of "Color Systems in Art & Science". This book represents an approach to the investigation of color that is aligned to our commitment to the arts as well as our development of custom products for artists. Each theory serves as an answer to a problem and each solution creates more problems and more potential discoveries.

Color theory, in all its forms, can act to direct the creative process. The color systems, as developed in this book, have been offered up by artists, philosophers and scientists, whose work towards this effort has spanned more than three centuries. They have contributed their observations and their conclusions for our evaluation. Though all of these theories are "correct", each investigation misses the mark to some degree. There is no unified theory of color, just as there is no absolute beauty or truth. In its simple, yet elegantly abstracted form, "Color Systems in Art & Science" summarizes so much of the critical thinking on color in one volume. The short descriptions of each theory allow one to begin to grasp the sum of these speculations.

Our lives at Golden Artist Colors have been devoted to the creation of color. We use many of the color methods illustrated in "Color Systems in Art & Science" as second nature, without giving much pause to their derivation or lineage. We use these guides as maps for direction or as definitions, allowing us a common language to describe

these abstract ideas of color amongst ourselves and with painters, printmakers and other artists.

The contributors to "Color Systems in Art & Science" have allowed us, through their research of a subject so ostensibly simple yet complex, to reexamine our thoughts on color. For those of you who enjoy the challenge of engaging the many theories that surround the subject of color, this book will provide a wonderful reference for further study as well as a guide for further exploration. For those of you who love color in art but believe theory has no place in creativity, I hope this book will provide some new insights for your involvement with color.

Mark Golden

INTRODUCTION

Many paths lead to an overview of the colors of our world. Artists and scientists have traveled along two of them. The scientific traveler may branch off onto additional routes along the way, by making a survey from a chemical standpoint, proceeding on the basis of physics, following physiological clues, making genetic analyses, pursuing the various possibilities offered by linguists and psychologists, not to mention those of the very individuals who seek to measure colors themselves, the colorimetrists. Colors offer a broad playground for human curiosity. Since antiquity countless attempts have been made to master their diversity and make them comprehensible via a color system or a color theory. Exhibition and catalogues provide a look at the history of such endeavors, as well as an overview of the course of their development.

One fascinating aspect of these color systems is that along with their external diversity they harbor two internal diversities. Laid out and intermingled here are the ideas of philosophers, poets, painters, physicists, physiologists, psychologists, textile manufacturers, chemists, entomologists, and colorimetrists. They originate from many different countries: England, Sweden, Switzerland, the United States, Germany, Italy, Hungary, France, and so on.

Every color system here represents one more in an ongoing series of unsuccessful attempts to capture the free kaleidoscope of colors in a geometrical cage. Every possible manner of ordering is in evidence, toward the ultimate (and

unattainable) goal of arranging colors so as to have equal gradations seen or perceived in every direction within a geometrical construction. To this end, lines and arcs, circles and squares have been laid down, or we encounter spheres and cones, cubes and cylinders, until finally we are confronted with really complicated three-dimensional constructs, derived on the basis of mammoth calculations.

Each effort was intended as an ultimate color system, achieving a harmony of colors. The creators of these systems apparently did not realize that they had taken on an impossible task. Colors exist because of and upon a background. This basis becomes lost as soon as one separates the colors from their natural situation and places them alone next to each other, as happens—and must happen—in setting up any color system. Of course, many color systems serve their individual purposes, but they all fail to provide a general, universally valid scheme of colors. Such a scheme is as impossible to determine as the long-hoped-for law for their harmony, thought to exist within some hypothetical definitive color order.

To visualize the history of the development of color systems in a straightforward way, let us begin with a simple line. Aristotle sought to organize his impressions along a straight line. Next, we proceed to Newton, who at the beginning of the 18th century bent this two-dimensional representation into a circle (Chapter 6). Then we come to Philipp Otto Runge, who at the beginning of the 19th century presented the color sphere (Chapter 13), the representation which we still find the most satisfying today. Indeed, we ultimately need three dimensions to encompass the three parameters required to characterize a color scientifically: hue, brightness, and saturation.

The diversity of color systems has been mentioned, but it must be emphasized that the variety illustrated here is only a portion of the manifold systems that exist. And their number continues to increase. It seems as though a new system appears every week, along with new problems and opportunities for dealing with colors, for example in making color photocopies or projecting overhead transparencies. It is not possible even to approach a complete coverage of all color systems, and this exhibition is limited to fifty-six. Along with these some "pre-systems" are offered. Their originators did not design them with any systematic order in mind. Likewise, some novel personal interpretations of "metasystems" are provided as an addendum; these are descriptions intended to elucidate how certain cultures or thought traditions have dealt with colors and have used them symbolically. Of course, the number of systems presented here is arbitrary, and was largely determined by the amount of space offered to Narcisco Silvestrini for his contribution to the 1986 Biennale in Venice. For this exhibition he was commissioned to compile and illustrate "sixty color order systems" in a conception that unified science and art. Silvestrini's work for the Biennale became the basis of this book—an attempt to tell the story of the development of color systems, considering the scientific and artistic aspects side by side.

The essential point is that the pictures were made by an artist and the text written by a scientist. The two cultures meet here, as they really ought to have met in a dialogue in Venice. But despite our good intentions, the two realms confronting each other here remain more or less irreconcilable. Above all, it is the colors themselves that demonstrate the different approaches to reality taken by the

representatives of the two cultures. The manner in which the great English physicist Isaac Newton approached light and its colors (Chapter 6), is patently different from the way the great German poet Johann Wolfgang von Goethe dealt with colors (Chapter 12). The important thing to understand is that in this book—as everywhere—one approach to color never wins out over the other. Instead what is involved are two equally justified descriptions of different aspects of one and the same world, and only together can they provide an adequate picture of reality.

For us, colors are not simply a given entity. Stated provocatively, in reality colors do not even exist. Granted, the colors we see depend on the light reaching our eyes from the external world. But perceptions such as red or green are first formed deep within the brain. Colors are not merely "actions of light," as Goethe once put it. They are also always "actions of the self." We decorate our world with them, and we do this only for ourselves.

The simplest way to think about colors is to consider them as ideas. Of course, it is clear that a chemist would first think of a specific dye, a physicist would primarily conceive of a well-defined wavelength, and a painter would visualize a precisely identifiable bright substance on the palette—to mention just some of the possibilities covered by the word "color."

We can only define what "color" is with precision by specifying its context. Colors are features (in biology); substances (in the dyer's shop); molecules (in chemistry); wavelengths (in physics); sensations (in psychology); and observations permitting a distinction to be made between unstructured patches of the same size and shape (in colorimetry). Colors can be all sorts of properties of the objects

making up our visible world, except for being an objective property.

The word "object," incidentally, was first coined in the 17th century, as men like Francis Bacon, Galileo Galilei, Johannes Kepler, René Descartes, and others brought about the revolution in thought that established our modern empirical or scientific view of the world. In this way of considering it, one separated the self from the external world, which then confronted our senses, i.e. as objects or things which literally "throw" themselves at us or oppose us. During this period, color also became an "object" of research, and Aron Sigfrid Forsius soon proposed the first color system (Chapter 1). He used the two achromatic colors black and white, together with four primary colors familiar to us all—red, yellow, green, and blue—adopting this set of basic colors directly from Leonardo da Vinci. But even the Italian artist had already questioned whether green was really necessary, since this color could be produced from a mixture of yellow and blue.

Leonardo probably would have been astonished to learn that his way of mixing colors on his palette is not the only way it can be done. In fact, when a physicist mixes light, he can obtain light yellow from red and green. This result is explained by the difference between additive and subtractive color mixtures, a difference understood since the 19th century (see, for example, Chapter 18). Even so, this merely distracts us from the problem which interested da Vinci and so many others, namely how many primary colors there really are. How many basic colors are sufficient to produce the entire kaleidoscope of light?

It is clear that there is an infinite variety of color nuances distinguishable by our eyes (with the help of our brain, of

course). But it is equally clear that our organ of sight does not have an infinite number of different receptors available for this multitude of colors and that the signals absorbed on the retina are not processed by our brain with an infinite number of nerve cells. The question of how many primary colors are needed to produce the nearly unsurveyable multiplicity of colors of the world is one of the main themes running through the history illustrated in this book. How many elementary colors are needed to name, reproduce, distinguish, and order all the other derived colors? How many basic or primary colors, "ur-colors" or whatever else they may be called are sufficient? Could it be that there is actually a scientifically precise answer to this question?

Biologists, neurologists, and geneticists all have answers, but there is no definitive answer which could make the other answers superfluous. The standard scientific explanations go more or less as follows: in the eye—more precisely on the retina—humans who are not color blind have three color pigments that are sensitive to the wavelengths one commonly identifies as red, green, and blue. While in the 19th century it was thought that what was valid for the brain was also true for the retina, it is known today that vision is not really that simple. Behind the retina the light-sensitive cells are connected to appropriate neurons which bring the brain the message that light has arrived on the eye. This transpires in such a way that red and green are mixed, so that yellow can then be transmitted along as a pure sensation.

In other words, while in the eye all colors are reduced to three components, the brain operates with the very four colors which we accept as primaries for the no more trivial reason that our language gives them the simplest names:

red, yellow, green, and blue. It is no coincidence that the first color system documented in the history of science operates on just this basis (Chapter 1). And it is even less of a coincidence that the recently presented Natural Color System (Chapter 48)—also originating in Scandinavia—again works with the same four elementary colors. The Natural Color System is based on these colors because it attempts to provide a practical and general method to describe color perceptions.

As this system was being prepared, two others were available as models, and the preparers wished to incorporate their advantages while avoiding their weaknesses. One, by the chemist and Nobel Prize winner Wilhelm Ostwald (Chapter 30), had a most convincing regular structure—the double cone. The other was the system of the painter Albert Henry Munsell (Chapter 29) with its remarkable and unique color tree. On the one hand, this color tree had an openness which indicated that color systems are going to be confronted with new color nuances produced by technologies of the future and must be able to classify and incorporate them. But it was too irregular for the creators of the Natural Color System, and this stimulated them to produce their solution as shown in Chapter 48. It resulted from what is generally called a phenomenological approach, which followed a procedure based on the proven fact that any surface color can be specified by its similarity to the four elementary color sensations red, yellow, green, and blue.

The proponents of the Natural Color System actually believe they are orienting themselves completely to natural circumstances, thus to all appearances leaving no wish unfulfilled. However, just as there can be new colors arising

from new technology, there can also be new insights from new sciences. And the new science which right now dominates is found in genetic research. It provides ever more exact knowledge about the organization and function of human genes. It has been possible not only to explain every variety of color blindness by a genetic mechanism (involving recombination), the increasing precision of genetic methods has also shown that we can no longer assume that all people have the same three color in their eyes. Instead there are individuals whose genetic variations permit them to possess two (or even more?) different pigments for the wavelength we usually associate with the sensation red. That means that these people see red differently from the way it had been previously described for the scientifically measured normal case. Their perception is richer than is permitted by the standard models, and it can be assumed that this discovery is only the beginning. Today it is only possible to speculate about what fine details in color sensations in the brain itself that will eventually be discerned using genetic analysis. A whole new diversity of the internal wealth of colors may open.

The crucial point is that with these discoveries from genetics a direct pathway has been found which leads from the world of molecules in the body (genes and their variants, but more directly their protein products) into the world of color perception and permits its analysis. The Natural Color System would of course only be appropriate for people with one red pigment (and similarly only one for blue and one for green light). It may turn out that future progress in genetics will show that completely different color systems are much more "natural." Perhaps the chance will ultimately arise to develop a color system to which we

can truly assign the term "genetic," one worthy of the broader meaning this word has long had in the history of ideas. Such a genetic color system could never be completed definitively, and instead could evolve and change with new scientific developments. It would have to be as open as the physical spectrum of colors is and at the same time appear as closed and complete as the circle of colors our brain constructs from this spectrum (which appeared for the first time with Newton—see Chapter 6).

With this hypothetical genetic color system one worthwhile goal might come into reach—namely, to do science for art's sake and to perform science as art. It remains to be seen whether this will turn out to be possible with colors and genes. But when such a possibility remains open, nothing is concealed. Then one sees better the colors involved. And they are so beautiful that it always will be worthwhile simply to enjoy them.

Ernst Peter Fischer

1 ARON SIGFRID FORSIUS

The oldest true color system originated from the Finnish astronomer, priest, and Neoplatonist Aron Sigfrid Forsius (died 1637), sometimes also known as Siegfried Aronsen. Forsius became a professor of astronomy in Uppsala, Sweden in 1603, later moving to Stockholm and beyond as a pastor. In 1619 he was removed from office after being accused of making astrological prophesies.

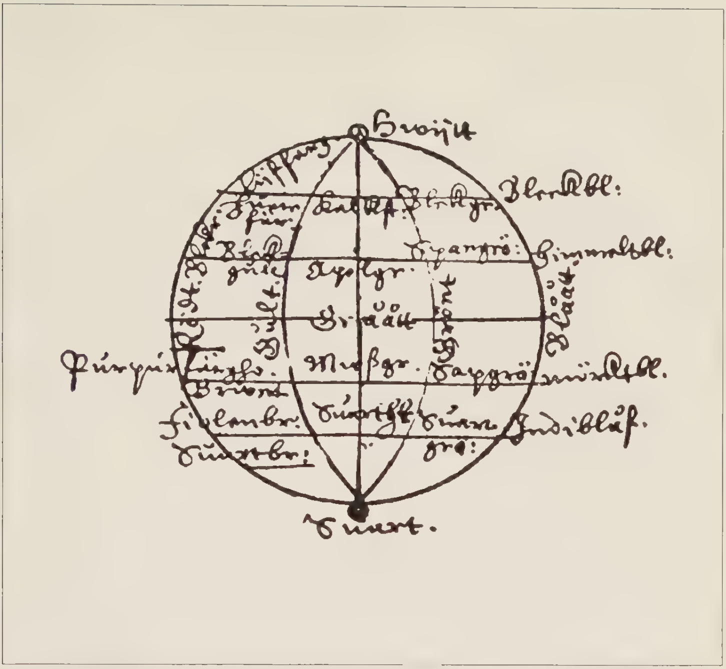
In a manuscript appearing eight years earlier, in 1611, Forsius expounded his thoughts on colors, with the conclusion that they could be brought into a spatial order. This text lay undiscovered in the Royal Library in Stockholm until this century, and was eventually presented in 1969 before the first congress of the International Color Association. In this work on physics Forsius introduced his color diagrams in Chapter 7, which was devoted to vision. He first discussed the five human senses, explained (in a rather complicated and incomprehensible way) how colors are seen, and then arrived at his color diagrams, in which he attempted to provide a three-dimensional picture.

Forsius wrote, "Among the colors there are two primary colors, black and white, in which all others have their origin." Here Forsius was in agreement with Leonardo da Vinci who, more than three hundred years earlier, had included black and white among the colors, seeing them as primary colors alongside yellow, red, blue, and green.

Forsius then continued, "In the middle, between these colors (black and white), red has been placed on one side

since classical antiquity, and blue on the other; yellow then comes between white and red, pale yellow between white and yellow, orange between yellow and red . . ." and so forth, until he had completed the whole circle. Around it we have placed the English translations of the Swedish names appearing inside (American terms because the Forsius manuscript was unearthed by American academics). Following this circle in Forsius's text is a drawing which was clearly intended to represent a color sphere. We have placed a version with English translations below the original Swedish version. Forsius used four basic colors (red, yellow, green, and blue), which he saw, together with gray, as "median colors" between the two extremes of black and white. With regard to his second diagram, he commented: "If, however, the origin and relationship of the colors are to be correctly observed, one must begin with the five basic median colors, red, blue, green, and yellow, with gray from white and black. And one must heed their gradation, and whether they approach white because of their paleness or black because of their darkness."

In other words, Forsius had the idea of introducing four basic chromatic colors, applying for each color a gray scale which runs from light to dark along the central axis of the sphere. The colors on the sphere's surface are arranged in such a way that three opposing pairs are created—red and blue, yellow and green, white and black. As we shall see, Forsius had thus paved the way for the modern color systems (even though the complementary colors were only later more exactly described). But looking at the colors of the Forsius sphere, we can see that its author had some difficulty with the overall perspective:



White

Live color—tree and wheat color—chalk gray—pale blue

Pale red—pale yellow—dapple gray—span green—sky blue

Red—yellow—gray—green—blue

Purple—flame yellow—mouse gray—grass green—dark blue

Violet brown—black brown—black gray—black green—indigo blue

Black

Forsius's color sphere was just one of the numerous attempts made in the 17th century to create comprehensive color scales. These were undertaken, in part, to permit very exact differentiation between the various styles of different painters. A technical problem which initially remained unsolved—also in Forsius's case—concerned a coordinated relationship between the two parameters color hue and

color value (or brightness). Pure yellow is simply brighter than unmixed blue.

The English doctor Francis Glisson is credited with the creation, in 1677, of a color solid which, in this respect, was both coherent and of sufficient quality to have become the ancestor of all color systems of the modern age. But according to John Gage in his *Culture and Color,* the success of Glisson's undertaking was unfortunately not recognized. He operated with the primary colors red, yellow, and blue, and his gray scale was composed of 23 steps between black and white, which he constructed using lead white and India ink.

Scientific progress was soon to surpass those mixtures developed by Glisson in his "scale for red" *(Scala Rubedenis)* or his "scale for black" *(Scala Nigredinis)*—progress initiated by experiments conducted even while Glisson was mixing his pigments. And as we shall soon see, at the end of the 17th century in Cambridge, Newton separated the white light of the sun, the first observer to subject colors to the scrutiny of physics.

FRANCISCUS AGUILONIUS

Franciscus Aguilonius (1567–1617) "was a Jesuit in Brussels and published his *Optics* 1613 in large format in Antwerp," as Goethe recounted in his *Theory of Colors,* adding "One can see in his achievement the quietness of the monastery, permeating the smallest detail of the work." We could also add that the origin of the rounded arc of his color system is also seen in the arched vaults and windows of the cloister.

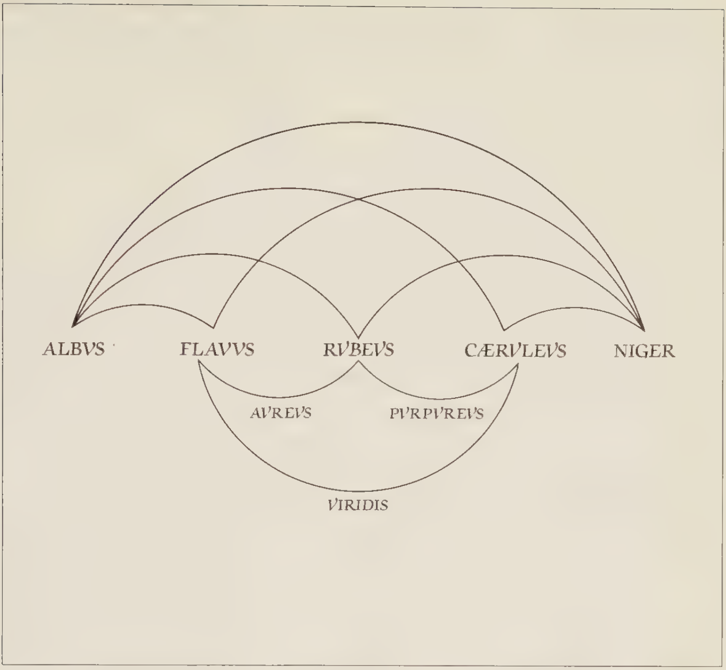
It is clear that François d'Aguilon (his French name) also conformed to the tradition of Aristotle, using the arc as a supplement to the classical linear division in order to specify all the possibilities of color mixtures. It is important to note that in his treatise on optics, which appeared between 1606 and 1611, Aguilonius was not merely seeking to visualize the artistic "colores concreti." He was more interested in the visible color qualities which this analysis brought the light.

His scale is based on an attempt to transfer musical consonants into the area of color. In doing this, Aguilonius did not concern himself with harmonies, but simply with the relationship between the colors. As a physicist, he had introduced the expression "simple colors," meaning any color from which an infinite number of other colors could arise through mixing. As our illustration shows, there are five of these simple colors, and three more can be directly composed from these: "Quinque sunt simplicium colorum species, ac tres compositiae," as he stated in Proposition 39

of his work. Between the extreme colors ("colores extremi"), defined as light and darkness—named *albus* and *niger* or white and black—come the median colors ("colores medi"), *flavus-rubeus-caeruleus,* yellow-red-blue. If two of the simple basic colors are mixed, as indicated by the arc joining them, then *aureus, purpureus,* and *viridis,* gold, purple, and green, will be formed. But Aguilonius explicitly warns against mixing all three simple colors, since only a murky gray hue will result—a "corpse-like color."

Aguilonius was praised by Goethe, since he expressed with unusual clarity "that the colors must be arranged according to the differing ways in which they appear." At the same time, Aguilonius differentiated—in Goethe's German translation of his work—between "true, apparent, and intentional colors" which the poet explained in his *Theory of Colors* as follows, "The true colors are allocated according to the properties of bodies; the apparent colors are seen as unexplainable, indeed a divine secret, yet to a certain degree they must also be regarded as coincidental." The intentional colors are still more difficult to distinguish, since, according to this interpretation, they are granted a will and a purpose—indeed a "spiritual nature, due to their delicateness and effect." Goethe devoted an entire chapter to them.

Aguilonius also applied the three-fold division of colors to their mixtures, and here the above concepts are easier to understand. Intentional mixing ("compositio intentionalis") merely involved the superposition of numerous colors. In addition, Aguilonius defined the combination of physical pigments ("compositio realis"), as well as the distribution of the smallest color patches ("compositio notionalis") that can be perceived by the eye as a mixture, although his diagram does not show these very clearly. His arcs can



certainly not be used in all three cases, since a mixture of yellow and blue light produces white—not green as he portrayed regarding the reflected light of paints.

In the jargon of the Neoplatonists, among whom Aguilonius is counted, it could be elegantly stated as follows: "The color diagram shows the relative position of the simple and composite colors on a scale which specifies their respective status through each color's participation in light." In his case, in accordance with the added proportions of white and black, all colors also exhibit different degrees of intensity.

The diagram suggests a continuous transition from the subdivision of the straight line, as indicated by the sequence of colors, to the continuity of the arc joining black and white—colors can also be used to create geometric patterns.

Aguilonius's system used three basic colors, and thus can be seen as the forerunner of all similar systems. In the pure combination of colors, he had dispensed with the fourth, green, which had already caused difficulties for Leonardo da Vinci, but not without granting it a special position. Like red (above), green was placed in the middle (although below). These two colors thus stand opposite one another, and rightly so, since they are complementary, as Aguilonius tacitly implies when he allocates a tip (a point) to red, while green is allowed to extend outwards as an arc. So a restrained point of color stands opposite the continuous colored line, for us to combine using the stepped diagram.

While working on his optics textbook *Opticorum libri sex,* Aguilonius had collaborated with the Flemish painter Peter Paul Rubens, who at that time (1611) was painting *Juno and Argus,* his famous visual allegory. Included in the picture are a rainbow and a peacock, and many have marveled at the fullness and abundance of their colors. In the second century A.D., the Gnostics had already made the astounding observation that the infinite fullness of colors in the tail of a peacock all emerge from a single white egg, and bestowed upon this fact the title "the greatest of all mysteries." In our modern age, this display has been reduced to the commonplace.

The idea that the potential for all colors is contained in white is thus ancient. It emerges clearly in a 13th-century treatise attributed to Albertus Magnus, which states: "Appearing in white are absolutely all the colors which mankind can imagine on the face of this Earth." Isaac Newton bought the collected works of Albertus Magnus in 1669—before embarking on his famous experiments dedicated to just this insight.

3 ROBERT FLUDD

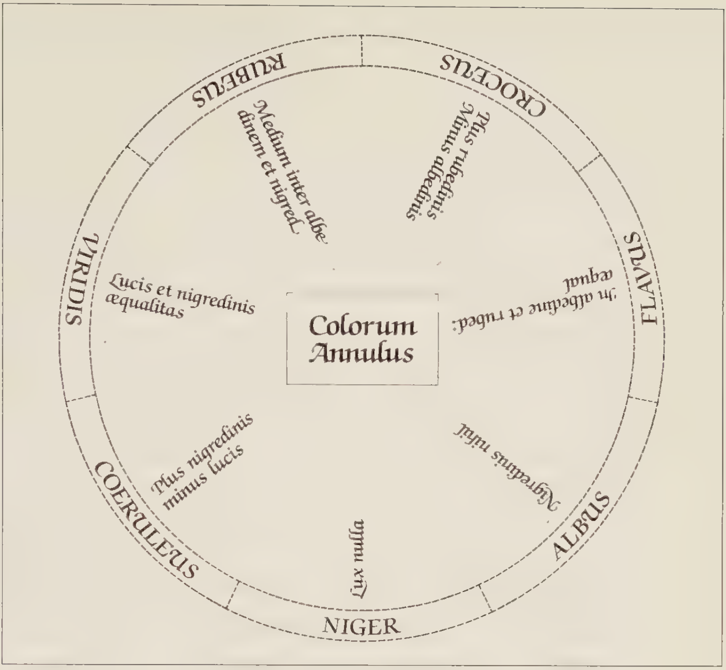
Around 1630, barely twenty years after A. S. Forsius published the first hand-drawn color circle, the first printed color circle appeared, in a medical work by the Englishman Robert Fludd (1574–1637). His color wheel had a total of seven areas around its circumference, pointing to its ancestral link with Aristotle's line. Fludd distorted this line, joining it back upon itself. He placed black and white *(niger* and *albus)* directly next to each other, with red *(rubeus)* opposite them, as a "medium." All three were granted the same status as four other colors: green *(viridis),* blue *(coeruleus),* yellow *(flavus),* and orange *(croceus).* Fludd, who also called himself De Fluctibus, was the author of a total of 20 works in Latin—including *The History of the Macrocosm and the Microcosm*—that contain many ideas which for us are incomprehensible. He took an opposing view to Johannes Kepler, and introduced three principles of the world: darkness, water, and divine light, the last giving life to everything. His work with colors appeared in a book in which he attempted to create a "Medicina Catholica." Although Fludd had intended to produce a universal medical text, only one volume ever materialized, in 1629–1631.

Throughout its two hundred pages, Fludd was occupied with diagnosis based on his observations on urine. From its color and consistency, he attempted to draw conclusions about a patient's health. His basic approach, which lasted into the modern age, rested on his conviction of the

existence of a metaphysical duality, manifest on Earth by the opposite poles of light and darkness. The purpose of his color circle ("Colorum Annulus") was to trace each color back to this duality. He also made the fundamental observation that colors are not merely coincidental ("as the ancient philosophers would maintain") but essences with which the Maker imbued his creations—the colors of things are part of their elementary make-up.

Fludd assigned values to the basic colors within his circle by establishing how much "brightness" (light) and "darkness" (blackness) was represented in them. White is light without blackness *(Nigredinis nihil),* and black is an absence of light *(Lux nulla).* In green, there is an equilibrium between light and blackness, and in yellow there is a balance between white and red. Orange originates when, in yellow, red increases relative to white, and sky blue will arise if, in green, the blackness increases relative to light. We have indicated these traces of Aristotle's theory in a second diagram.

So Aristotle's ideas continued to be influential. At this point a short digression from the 17th century seems worthwhile. In essence, we note that color theories from antiquity relate to a few basic colors and their corresponding mixtures. Our understanding of these theories is hindered by the fact that our language is almost incapable of expressing the various names used for colors in Greek or Latin. Translators of Aristotle's texts, for example, have regularly pointed out that the same word was often used to describe various tints. This is partly because many color names did not primarily describe a color hue, but rather the material from which the color can be extracted. Individual words thus cover a whole range of different brightnesses or



brilliances not implied by our modern (standardized) color terminology.

Aristotle (384–322 B.C.) had three predecessors, who all began their classifications with four primary colors. Empedocles (circa 500–430 B.C.) chose white, black, red, and yellow ochre, to which he assigned the four elements: fire, earth, water, and air. The only certain associations here, however unusual they may appear to us, are of white with fire and black with water. Empedocles's interest was in chemical composition, as it would be called today, while Democritus (circa 460–370 B.C.) adopted more of a physicist's perspective, emphasizing certain atomic relationships. He likewise specified four basic colors, but replaced yellow ochre with a greenish yellow. In addition to his primary colors, he specified color mixtures derived from

these—seven in all: besides yellow-red, purple, indigo, leek green, and dark blue there were a nut color and a "fire" color which we can imagine was a bright brown-yellow.

Plato (427–348 B.C.) kept these four basic colors (white, black, red, and "radiant"). Neither chemistry nor physics were important to him. Color was basically an element of beauty, and its brightness should enhance its effect. Aristotle, in turn, was more practical. He restricted the basic colors to the two extremes of black and white, defined by either the absence or presence of light. Light on its own was thus white, and for that reason he assigned this color to the element air. This is an important point: in Aristotle's case, (in *De sensu et sensibili*) light itself was colorless. Light is only the medium by which colors can be seen—those colors which objects actually possess. Colors only appear when a body is no longer transparent. For Aristotle the many colors of the world were produced by mixing. This took place on various levels. The five colors of his scale were formed from black and white—yellow, scarlet, purple, leek green, and dark blue—and these in turn could be mixed. The secondary colors arise from the juxtaposition of the smallest points of basic colors, no longer perceivable by the human eye; from the superposition of basic color layers, or through blending colored substances.

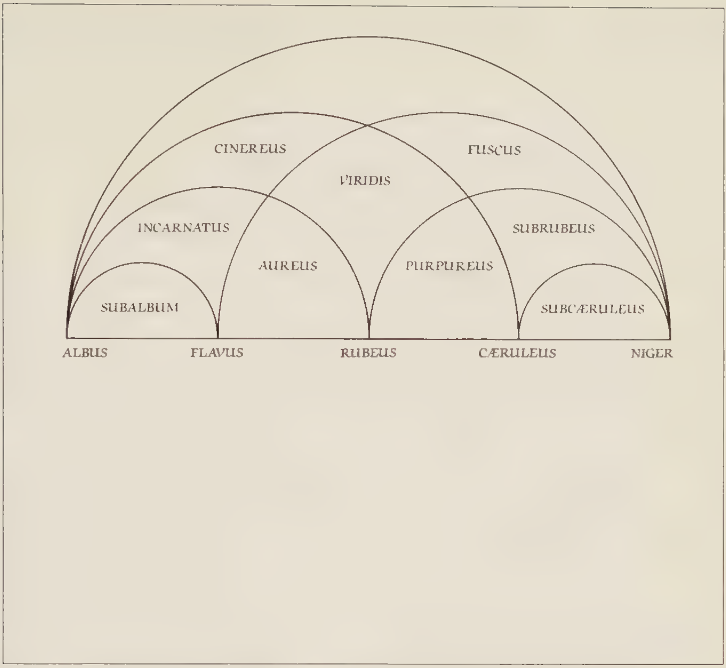
Aristotle's theories remained influential up until the time of Fludd in the early 17th century, and their influence was not confined to Europe. They also intensively occupied the Arabic philosophers, who re-examined the relationship between light and color in the 11th century. Avicenna (980–1037) disputed the existence of colors where darkness prevailed, since without light the vital "verum esse" would be denied them. His rival Alhazen (965–1038) took

the opposite view—that colors did indeed exist in the dark, but did not reach the eye.

In Europe, Roger Bacon (1214–1292) looked into this question in his own research, declaring that light and color only occur when combined: "Lux . . . non venit sine colore."

ATHANASIUS KIRCHER

Athanasius Kircher (1601–1680) came from Fulda in Germany. He was a versatile man whose activities included teaching mathematics and Hebrew. He also attempted to decipher Egyptian hieroglyphics, and invented the concave burning mirror. More than forty works by Kircher have been passed down to us, One appeared in 1646, specifically devoted to colors—*Ars magna lucis et umbrae* (The Great Art of Light and Shadow). His system provides a concrete example of mixed colors, characterized by semicircular arcs. These are the basis for all combinations; a linear construction which, apart from white *(albus)* and black *(niger)*, operates with three primary colors: yellow *(flavus)*, red *(rubeus)*, and blue *(caeruleus)*. We need not list all his arrangements here, and neither should we attempt to translate all the many novel names—like *subrubeus*, or *fuscus*, or *incarnatus*. The special position of green *(viridis)*, however, is noteworthy. Like red, green is placed in the center, although on the plane of the mixed colors, and not the pure colors. Green is located at the overlap of yellow and blue. If we draw the arcs running from white so that they are directed upward and the curves to black so they run down, an image will be created which resembles the Chinese Yin-Yang. (To create this symbol, we need only retain the route through red, while omitting the lines passing through yellow and blue.) As our illustration shows, all the color points of this system can then be reached from white and black, and this should make its author's fundamental



view apparent. In fact, Kircher viewed color as a "genuine product of light and shadow," as he wrote in the forward to his 1646 book, adding that color is "shady light" and "everything in the world is visible only by means of shady light or illuminated shadow."

Kircher's book contains eight chapters, which deal with the multitude of colors, investigate the colors of transparent stones, and consider those of plants and animals. For example, Kircher wanted to know why four-legged animals are never golden-colored, while insects and birds can adopt all of the colors. Kircher also pondered why the sky appears blue—without arriving at a satisfactory explanation.

The mechanical aspect of the sky's blueness can in fact be explained by modern physics, which tells us that light reaching us from the sky is scattered. This means the rays

of the sun collide with particles in the atmosphere and are diffused by them. If this process is examined in detail, it can be shown that different components of light are scattered differently, so that blue light predominates. This is because of its shorter wavelength (i.e., higher frequency). This scattering occurs to such an extent that ultimately only the blue light reaches our eyes. (To be more exact, physicists can demonstrate that for very small particles scattering light, the intensity of diffused light is proportional to its frequency, to the power of four. And that is why the sky is blue, at least according to the lessons of physics.)

But Kircher was not, of course, seeking this kind of answer. Nor would he have understood it, had it been given to him. In Kircher's day, the physics of light and color still had to await their time, though he was aware of the prism and its effect on light. He accounted for the colors it produced by noting that the brightest occurred after passing through the thinnest side of the glass, and the darkest after passing through the thickest side. He was the last person, for a long time, to consider the brightness of the primary colors, and incorporate this aspect into his system. After more than 2000 years in use, the ordering of colors from bright to dark—as in Kircher's system—was lost, only re-emerging during the 20th century.

5 RICHARD WALLER

Just after the old order of colors from dark to light—or from black to white—had disappeared near the end of the 17th century, the Englishman Richard Waller tried to discover whether the colors could be arranged within a square. He published his attempts in order to provide a *Standard of Colors,* complaining that standard terms of reference had not been established among the philosophers. This was regrettable, he said, because the science of colors went beyond the demands of medical diagnosis, and now had to serve the added purpose of cataloging the Creation.

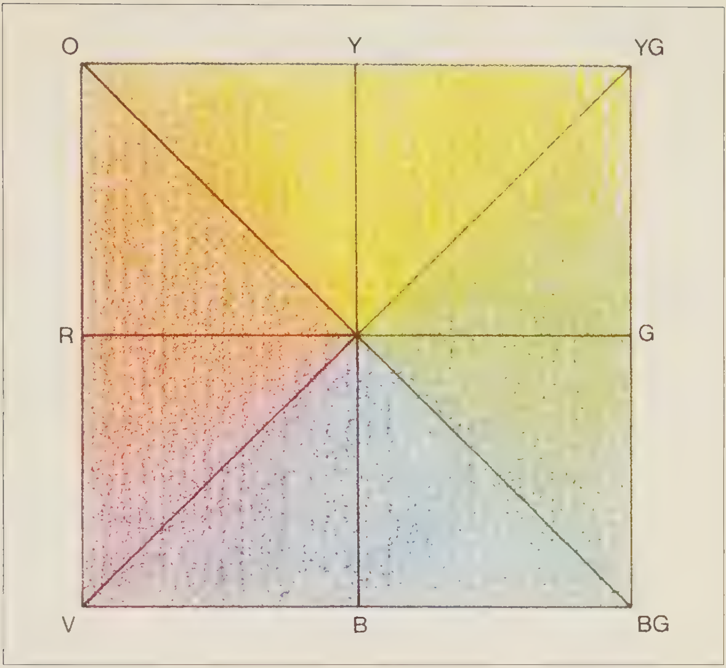
We reproduce Waller's system with its four primary colors—yellow (Y), red (R), blue (B), and green (G)—which were placed not at the corners of the square, but in the middle of each respective side. The resultant mixtures could then be entered in the fields of the grid formed. Waller did not determine these intermediate hues intuitively, but empirically, i.e. according to weight. In other words, he mixed the primary pigments in equal proportions or weights. If we separate Waller's square into primary and secondary lines, the diagonals are revealed as the locations of synthesis. The mixed colors—orange (O), yellow-green (YG), blue-green (BG), and violet (V)—will then result, in the physical sense, from the forces which generate the primary colors.

Waller published his system in about 1686 under the title *Catalogue of Simple and Mixt Colors.* His square represents the last obstacle on our way to Isaac Newton, who

had been occupied with his optical experiments since 1670, and had imposed a fundamentally physical way of thinking on the future order of colors. At this time, there was above all a change in the old viewpoint that the formation of colors resulted from white light modified by mixture with darkness. The new idea that colors are not actually changes imposed on white light, but are in fact its original components, was arrived at through experiments with a prism. In 1648, the Bohemian physicist Marcus Marci had used a prismatic glass for the first time. He allowed sunlight to enter a darkened room through a small opening, and then directed the resultant ray through a prism. He saw a series of colors, which we now call the spectrum, but mentioned only red, white, and violet. Marci noted that the modification depended on the angle through which the light was deflected, and also remarked that colored light cannot be subjected to further separation.

In Bologna, Italy, during the same period (1650), F. M. Grimaldi discovered that small openings will give a trail of colored light traces. Today, this phenomenon is explained by a process called diffraction.

The physics of color—prior to Newton—then gained real momentum with Robert Hooke, who began to investigate the colors which occur when light is refracted on thin fragments of mica or between glass plates. In his *Micrographia,* Hooke also made daring assumptions about the nature of light. For him, a wave motion was involved, and he believed that a wave surface perpendicular to the ray produced white light and that the inclination of this surface gave rise to color, which took effect on the edge of a light ray. Colors as the inclination of a wave surface—only a physicist could think of that! But the champions of science

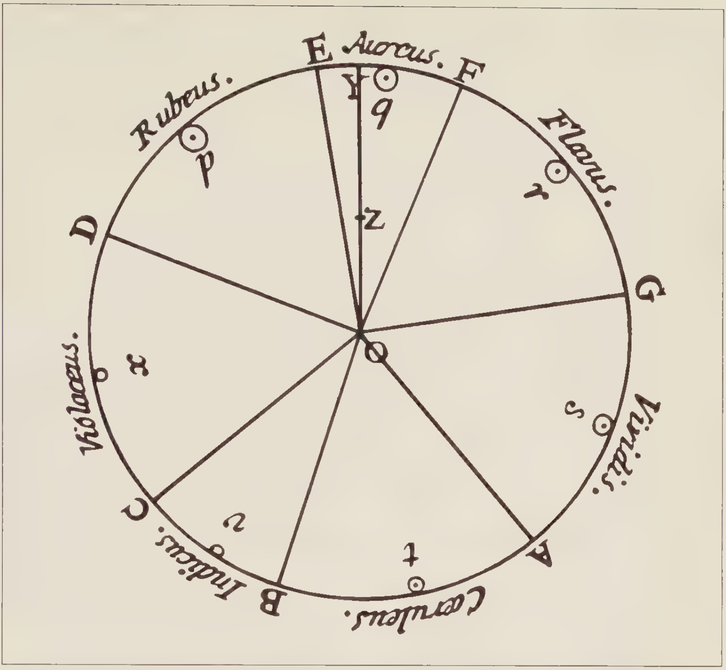


had yet more vivid ideas, and these will occupy us in the following pages.

ISAAC NEWTON

"Newton created white from all colors. Indeed, some of what he told you, he'd have you believe for ever more"—with that, the German poet Goethe challenged Isaac Newton, more than a hundred years after the British physicist had dispensed with the old organization and specified a new order of colors according to values of brightness and darkness. Newton had transformed the normal linear system into a circle. We can see that Newton's color circle comprises seven colors in the sequence red (p)—orange (q)—yellow (r)—green (s)—blue (t)—indigo (v)—violet (x). Black and white have been excluded from the sequence; instead the vacant center of the circle has been expressly given over to white, to symbolize that the sum of all the specified colors will result in white light. Goethe protested vehemently against this idea, attacking the very foundation of Newtonian optics, which is based on the separation of daylight into its components by a prism.

Isaac Newton (1642–1726) can certainly be counted among history's most influential scientists. His most productive period was during his youth. When he was just twenty-two years old, he had begun to develop his "method of fluxions," today known as infinitesimal calculus, which made possible the mathematical calculation of speeds and accelerations. Four years later, he constructed a reflecting telescope (to eliminate the irritating aberrations of its predecessors). It was also during these years that he gained



the insights for which he was to become famous—Newton was able to demonstrate that an apple falling to the ground and the moon orbiting the earth both obey the same mechanical laws. In other words, he showed that the physics of the earth is likewise the physics of the heavens. So the cosmos is not strange to us; our laws apply there, too.

In 1687, Newton published his greatest work, *Philosophiae Naturalis Principia Mathematica,* in which he put forth his ideas on gravitation and its mathematical treatment. By this time, he had also undertaken optical experiments, and had long since realized that white light was made up of colored rays. In a work submitted to the Royal Society in 1672, he presented "a new theory of light and colors." It was written the previous year, when the plague had threatened London and Newton had withdrawn for

several months to his parents' farm in the county of Lincolnshire. Here he began by repeating Marci's experiments (see Chapter 5). In 1648, Marci had directed white light through a prism and observed its deflections. Newton took this a step further, becoming convinced that the deflected light rays ran on in a straight line after passing through the prism. In his "experimentum crucis," Newton directed the rays which had been refracted by a first prism through a second prism. He observed that they were deflected once more, but were otherwise not altered (not further separated into colors). For Newton, this was proof that colors are not modifications of white light, but the original components of white light. Indeed, white light is composed of colored light, the colors those seven he placed in his color circle. These are not mixtures; each is a single pure color. It can be mixed, of course, to produce secondary colors. But if the right components combine in the correct proportions, the light will appear white.

The palette formed through the refraction of light by a prism is referred to as the spectrum, the components of which are the spectral colors. For Newton, the question was how to explain them? For what reason is blue light deflected (refracted) in a prism to a greater extent than red light? An answer could only be provided if more was known about the nature of light. What actually was a light ray, which evidently moved in a straight line? Did it involve a wave? Or did light comprise tiny particles (corpuscles)?

Newton attempted to clarify these questions in his second definitive work, his *Opticks,* which first appeared in 1704 and contained the color circle which we reproduce. The colors are indicated here by circular figures, the largest for red, becoming progressively smaller toward violet. In

this way, Newton reveals something of his ideas about the nature of light. He believed that light was composed of corpuscles which were deflected by a prism according to their size; the large red was subjected to the least deflection, and the small blue the most.

Let us now examine other details of Newton's color circle. Its colors are allocated to segments, the sizes of which are proportional to their particular color's intensity in the spectrum. Using this segment size and the varying sizes of the light corpuscles, a type of concentration point for the circle—marked as Z by Newton—could be calculated and marked in. The straight line, which connected the white color center O and this center of concentration Z, intercepted the circle at Y. Bearing in mind Newton's affection for mechanics, we see that color mixtures can then be represented by drawing a triangle of forces, the three corners of which are formed by the three basic colors: red, blue, and green.

Newton's view that light was composed of corpuscles contradicted that of the Dutchman Christian Huygens, who published his paper *Traité de la Lumière* in 1678. Huygens saw light as a movement within a fine medium, its motion triggered by shocks within matter, which in turn emanated light. A proponent of this wave idea four hundred years earlier was Robert Grosseteste, who had envisaged light spreading as a "species" ("multiplicatio speciorum"). Unfortunately, Huygens completely neglected the problem of how the spectral colors could be formed. The currently accepted answer, an increase in wavelength from blue to red, remained beyond his understanding.

Newton's color circle would remain inadequately explained if we ignored his belief that the propagation of light

and sound are comparable, and that they should therefore be treated harmonically in an identical way.

Newton selected his seven colors because an octave displays seven sound intervals. He allocated segments to them in accordance to their value in the Dorian musical scale. The individual sound tones associated with this scale coincide with the borders between the color grades: D, for example, is the border between violet and red, and A lies between green and blue. This mathematical-musical elaboration of colors makes it difficult for many to understand Newton's system. With its seven (instead of five) primary colors, it seems to have more of an aesthetic basis than a scientific one.

With Newton's color circle, the transition from the linear to the circular color system is complete. It is helpful to realize that although this step was made by a physicist, it actually has little to do with physics. The spectrum which Newton sees on the other side his prism is a line which he can only transform into a circle because the color tones merge into one another gradually. For this reason alone, and by dispensing with purple, the short-wave end (violet) can be joined onto the long-wave end (red). This omission in physics is overcome by our senses. Out of the straight line of the physical world, it is actually the human brain which creates this circle, first drawn by Newton. We can understand colors only when we also take into account the mind of those who see them.

7 TOBIAS MAYER

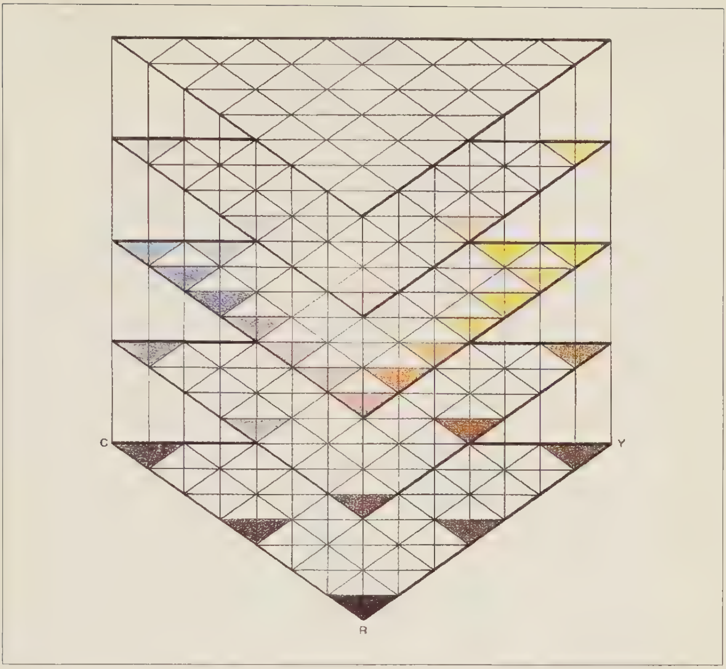
In 1758—more than half a century after Newton's *Opticks* had appeared—the German mathematician and astronomer Tobias Mayer (1723–1762) gave a lecture to the Göttingen Academy of Science entitled *De affinitate colorum commentatio*, in which he tried to identify the exact number of colors which the eye is capable of perceiving. He chose red, yellow, and blue as his basic colors, and vermilion, massicot, and azurite as their representatives among the pigments. Black and white were the agents of light and darkness, which either lighten or darken the colors.

For Mayer, it was clear that very small variations in color are not noticed by the eye, and for this reason the difference between mixtures cannot be selected freely. In order to have a basis for calculation, Mayer adopted twelve gradations—similar to an octave—between any two basic colors, and claimed that the mixing of a twelfth part of a color into a base color was essential in order to perceive the new mixture. He then made the following (rather obvious) note: cinnabar is characterized by *r12* (12 units of red), massicot by *y12* (12 units of yellow), and azurite by *b12* (12 units of blue). Mixtures are rated, for example, as *r6y6* (6 units of red and 6 units of yellow to give orange), *b6y6* (6 units of blue and 6 units of yellow to give green), or *r6b6* (6 units of red and 6 units of blue to give violet). By placing the pure colors *r12, b12,* and *y12* at the corners of a triangle, Mayer constructed a geometric figure which systematically shows

how 91 chromatic colors, for example *r4b5y3* or *r2b8y2,* can be created.

Tobias Mayer's color triangle was first published in 1775 by the Göttingen physicist Georg Christoph Lichtenberg —more than 12 years after Mayer's death—in an edition which included other "opera inedita"—at the suggestion of Johann Heinrich Lambert (Chapter 9), who had used the Mayer triangle three years previously. Mayer's original showed a planar figure with 91 compartments, but at the close of his lecture he had also mentioned that each of the constructed (mixed) colors could be modified toward bright or dark by adding up to four parts of white or black. The aggregate of theoretically distinguishable colors in his system therefore rises to 2 x 5 x 91, or 910. The position each color had is shown in the figure, with its superimposed triangles, as described by Mayer but not illustrated graphically. The basic triangle is located in the middle, with gray at its center. The proportion of black (BK) increases in the downward direction, with white (W) added in the upward direction. R stands for red, Y for yellow, and C for cyan blue. However, the construction does not work—it contains an anomaly. The gray center of the basic triangle is already so dark that the central area beneath it can only be repeated, and offers no further opportunity for gradation.

Mayer is still famous in the world of astronomy for his exact measurements, winning great acclaim for his methods of detecting instrument errors. His most significant contribution, made in 1760, was to show that fixed stars had their own motion, and are not actually quite as fixed as had been assumed up to that time. This observation owed something to the *Theory of the Heavens,* brought out in 1755 by the philosopher Immanuel Kant. It encouraged

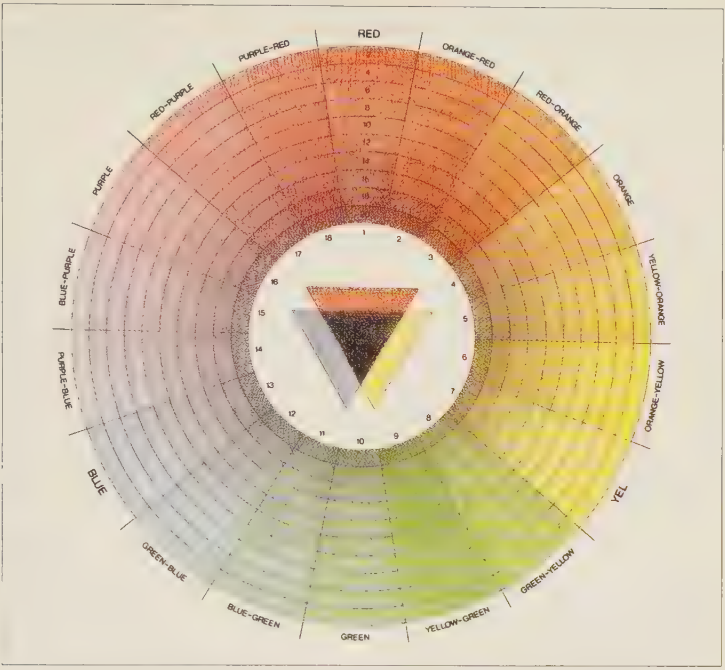


Lambert, the Alsatian naturalist mentioned above, to start (in 1761) his *Cosmological Letters,* in which he attempted to provide a new theory of the universe. Thus, Mayer twice provided impetus toward our contemporary world view—first with the stars, then with colors.

MOSES HARRIS

In 1766, one hundred years after Newton's separation of white light through a prism, a book appeared in England with the title *The Natural System of Colours.* In this work, Moses Harris (1731–1785), an English entomologist (insect specialist) and engraver, concerned himself with Newton and attempted to elucidate the multitude of hues which can be created from three basic colors. As a naturalist, Harris wanted to understand the relationships between the colors and how they are coded, and his book attempted to explain the principles, "materially, or by the painter's art," by which further colors can be produced from red, yellow, and blue.

Harris exploited the discovery of the Frenchman Jacques Christophe Le Blon (1667–1742), who is credited with the invention of color printing. In 1731, during the course of this work, he had been the first to discover something which every schoolchild learns today: that three paints: red, yellow, and blue, are sufficient to produce all other colors. Although Le Blon invented the fundamental three-color palette and demonstrated his system with many dyes, he did not extend his ideas to a properly organized color system—that was left for Harris to achieve. Harris introduced the first printed color circle in 1766, specifying his primary colors very exactly: red was the pigment cinnabar, which could be made from sulphur and mercury; yellow was royal yellow (an artificial orpiment); and ultramarine was used for blue. Harris differentiated between the harmony of the



"prismatic or primitive colors," which were assigned to a "prismatic circle", and "compound colors," which are allotted their own circle. The word "prismatic" may cause some confusion. In fact, Harris did not merely imply the spectral colors which Newton had observed and arranged in a circle. He meant the unmixed pigments ("grand or principal colors"). Mixtures ("compounds") of two of the three basic colors result in the three intermediate colors ("mediates")—orange, green, and purple—which also appear in the prismatic circle, and are all brought to life with natural descriptions ("fruit or flower"). According to Harris, the three main colors—red, yellow, and blue—are "the greatest opposites in quality to each other and naturally take their places at the greatest distance from each

other in the circle." In order to arrange this "greatest distance" evenly within the circle, Harris required an even number of circle segments, so Newton's seventh color, indigo, had to be dispensed with.

In his system of six colors Harris recommended mixing adjacent colors so that one of these two components predominated in each case. In this way, 18 colors will be generated to complete the circle, in sequence: red, orange-red, red-orange, orange, yellow-orange, orange-yellow, yellow, green-yellow, yellow-green, green, blue-green, green-blue, blue, purple-blue, blue-purple, purple, red-purple, purple-red. Harris subdivided each of his three initial colors with the aid of concentric circles into 20 different saturation levels, so his method creates a total of 360 hues in the prismatic circle.

Orange, green, and purple form the basis of the circle of mixed colors. These are mixed to form three tertiary colors—brown, olive, and slate—which are assigned to a similar ("compound") circle. Since the secondary mixed colors (orange, green, and purple) are already contained in the prismatic circle, this method of mixing yielded 15 new colors, which he again provided with 20 levels of intensity, resulting in 300 new colors. A total of 660 colors can thus be defined in the two circles (with only 33 names). The author expressively remarked that many of these "never will admit of being mixed together," since the result is merely "a dirty meaningless color," and unacceptable to many painters. At the center of his circle, Harris has illustrated what we now know as the subtractive mixing of colors. Here is his most important observation: that black will be formed through the superposition of the three basic colors, red, yellow, and blue. At this point, it is important

to emphasize that such a composition remained obscure to Newton, who mixed not pigments, but light rays. Newton added, while Harris subtracted. If confusion is to be avoided, additive and subtractive color mixtures must be carefully differentiated.

To explain what happens with Harris's subtractive color mixtures, we cannot just consider the spectral composition of light, i.e., the wavelengths. We must also take into account the impression of color created in our minds when only a part of the spectrum enters our eyes. In this case, it is evident that colors are never biased, and are always to be understood as an interaction—here an interaction of physics and perception.

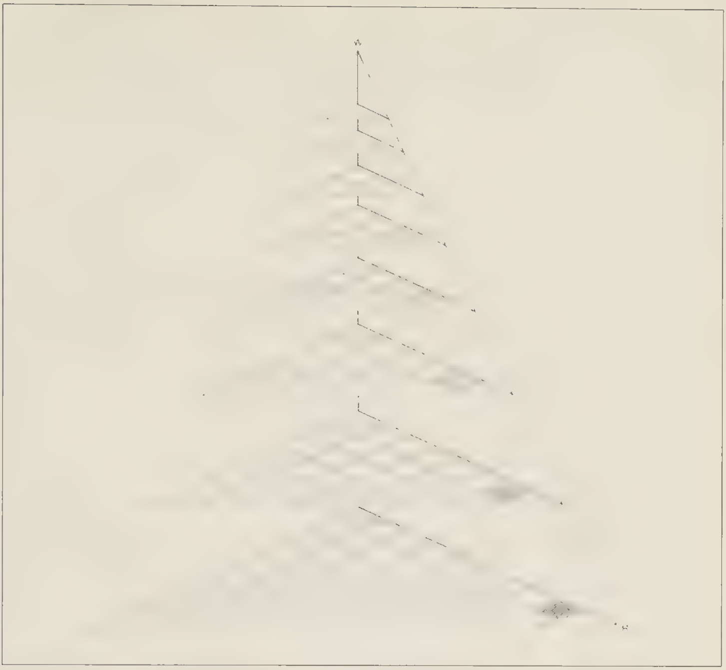
We can separate the whole of the visible spectrum into three areas: blue is short-wave electromagnetic radiation, green is medium-wave, and red is long-wave. A surface will appear to us as red when it reflects the long-wave spectral colors and absorbs what remains. A surface will appear yellow when it reflects radiation only from the medium and long-wave part of the spectrum, and will appear blue when only short and medium-wave light reach our eyes.

By superimposing one color on another, Harris progressively removed a component of radiation (subtraction). If yellow and blue are placed one over the other, only the medium wavelength will remain, and our brains will see green. If red and blue are superimposed, only the short-wave end of the spectrum will remain, giving us the impression of violet. If all three come together, then no component will remain—"Lux nulla," we could call the result, meaning the black appearing in the center of the prismatic circle.

9

JOHANN HEINRICH LAMBERT

The Alsatian mathematician and naturalist Johann Heinrich Lambert (1728–1777) is renowned among physicists as the founder of the theory of light measurement, or "photometria" as it was called at the time. In about 1760, Lambert originated the law—which still bears his name—mathematically describing the illumination of a surface by a light source. He also studied the ability of surfaces to reflect and their transparency. His *Cosmological Letters,* which he wrote as a member of the Academy of Frederick the Great in Berlin, remain classics among astronomers. In these writings, Lambert set out to explain the structure of the universe—at that time even the extent of our own galaxy, the Milky Way, was unknown. In the course of his deliberations, he consulted measurements made by Tobias Mayer in Göttingen, and thus became aware of Mayer's color triangle dating from 1758, the publication of which he would subsequently advocate. Lambert recognized that Mayer had discovered a means to construct and name many of the possible colors. At the same time he also realized that, to extend the triangle to include the full abundance of colors, the only element missing was shading, added in a third dimension, as depth. After carrying out his own experiments, Lambert suggested a pyramid, constructed from a series of triangles, to accommodate the full richness of natural colors in one geometric form. These differ from Mayer's triangles not only in their size, but also in the position of black. The corners of Lambert's base



triangle are, as with Mayer's model, occupied by royal yellow, cinnabar (shown here as Y for yellow and R for red), and azurite. In each level, two basic colors are mixed (in varying proportions) to form seven hues along the sides, while on the inside all three basic colors contribute to the color of the surface units. A total of 45 color hues are thus formed in the lowest triangle, above which the others rise, tapering and becoming brighter as they proceed upward. They contain successively 28, 15, 10, 6 , 3, and finally 1 field. In his pyramid, the tip of which is white, Lambert accommodated a total of 108 colors and mixtures.

This construction succeeded in incorporating the various "tertiary colors" into one system and logically linked them with the neutral gray values appearing along its central axis. The color created by mixing all three basic

colors—black—is found at the center of the lowest triangle. More colors can be distinguished on this plane than at the highest point, where white predominates, which is why the system of colors tapers going upward toward lightness, and thus forms a pyramid.

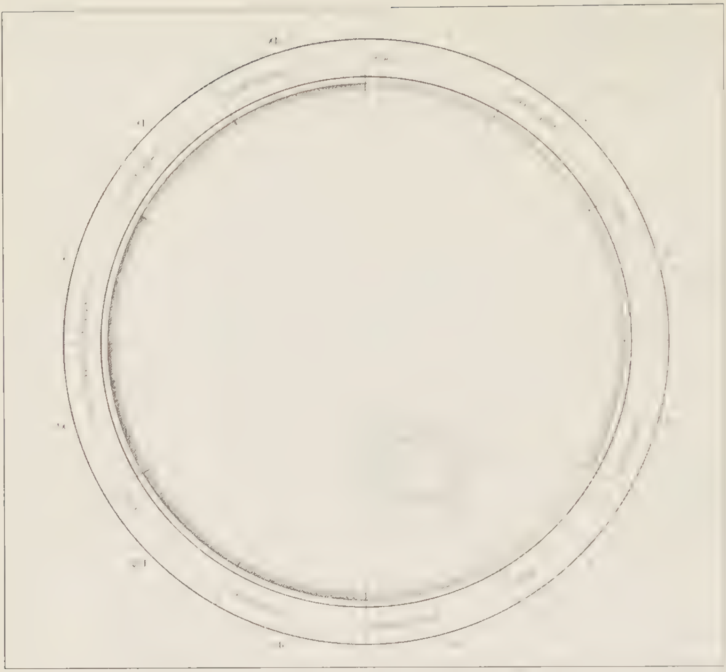
Lambert envisioned that textile merchants would be able to consult his system to ensure they stocked all the colors and locate any gaps in their range. He also hoped that the dyers and printers of his time would find inspiration for new mixtures.

As a naturalist, Lambert used his pyramid in his efforts to identify and classify all the colors which occur in animals and plants. Of course, this objective could only be achieved if a mixing system operating with the colors yellow, red, and blue is capable of creating every other color. But unfortunately, this is impossible. In nature, there are many tints of very colorful green, orange, or violet which cannot be arrived at by subtractively mixing three primary colors. Many hues in a butterfly's wing, for example, are not formed by a mixture, but through the physical property of light known as interference, which occurs as it passes through thin leaf-like structures, like butterfly wing scales. The abundance of colors which can be produced in this way reaches far beyond the dimensions of the pyramid in which Lambert sought to arrange them.

10 IGNAZ SCHIFFERMÜLLER

In the same year J. H. Lambert constructed his color pyramid showing for the first time that the complete range of colors can only be reproduced in a three-dimensional system, another color circle was published in Vienna by Ignaz Schiffermüller. The circumference of his circle is filled with twelve colors, named blue, sea green, green, olive green, yellow, orange-yellow, fire red, red, crimson, violet-red, violet-blue, and fire blue. The transitions are continuous—in marked contrast to those of Moses Harris—and the three primary colors of blue, yellow, and red are not placed at equal distances from each other; between them come three kinds of green, two kinds of orange, and four variations of violet (as distinct from the secondary color violet). So Schiffermüller selected a total of 12 colors, thus drawing upon the system originated by the French Jesuit Louis who had extended Newton's circle of seven colors to twelve. Louis's choices were unusual: *bleu, celadon* (pale green), *vert, olive, jaune, fauve* (pale red), *nacarat* (orange), *rouge, cramoisi* (crimson), *violet, agathe* (agate blue), and *bleu violant*. Like Newton, Louis linked his system to music—more specifically to the twelve semi-tones of the musical scale.

Schiffermüller's system served to illustrate Newton's discovery that the pure colors could be arranged in a circle. This Viennese entomologist was one of the first to arrange the complementary colors opposite one another: blue



opposite orange, yellow opposite violet, red opposite sea green. Schiffermüller also placed a sun (only faintly suggested here) inside his color circle, to emphasize that he wished to show "the radiant colors" produced by nature. He sought to achieve "vivacious and gleaming colors" like the wondrous colors of the rainbow and considered further combinations of "subsidiary colors" as aesthetically unsuitable.

By 1771, Schiffermüller felt it was time to treat colors as a natural system, and bestow upon them a kind of natural order, in exactly the same way as had long been done with animals, plants, and minerals. Such an order would have been an indispensable aid to the descriptive methods common among naturalists at the end of the 18th century. In his *Color and Culture*, John Gage recounted the story told

by the painter William Williams in 1787 about an entomological illustrator, who "living in a remote country, unacquainted with artists, or any rational system of colors, with a patience that would have surmounted any difficulties, had collected a multiplicity of [paint] shells of color, of every various tint that could be discerned in the wing of that beautiful insect [the butterfly]; for he had no idea that out of two he could make a third, by this method he had collected two large hampers full of [paint] shells, which he placed on each side of him, and sometimes the individual tint he wanted, was half a day's labor to find out. What excellence must he have arrived at, had he known how to mix his tints."

11 JAMES SOWERBY

At the beginning of the 19th century, the Englishman James Sowerby (1757–1822), already distinguished as an author of books on botany and natural history, introduced his color system, dedicated to "the great Isaac Newton." It had the lengthy title *A New Elucidation of Colors, Original, Prismatic and Material: Showing Their Concordance in the Three Primitives, Yellow, Red and Blue: and the Means of Producing, Measuring and Mixing Them: with some Observations on the Accuracy of Sir Isaac Newton.* Sowerby set himself two tasks with this work, which appeared in London in 1809. He wished to re-emphasize the significance of brightness and darkness, which after Newton had fallen into obscurity, and to clarify the difference between colors. As already shown, the colors of light and the colors of materials behave in a different way when they are brought together. Sowerby assumed the existence of three basic colors in his system—red, yellow, and blue—which were then combined. He selected gamboge (a poisonous yellow sap from certain Asiatic plants), carmine, and Prussian blue as his basic pigments.

The sketches emphasize the three parts on which Sowerby's theory rests, and express the stabilizing continuity which can exist between them. Incidentally, Sowerby's attempt to transform Newton's seven primary colors into three materially renderable basic colors attracted the attention of the English painter William Turner, and the two became acquaintances. Later, in about 1820, Turner tried —as had the painter Otto Runge—to assimilate the system

of the three colors red, yellow, and blue into a diurnal cycle. (There is more than one way to do this, as was soon apparent to him.)

Sowerby described the optical mixtures which resulted when narrow, tightly packed stripes of primary color were applied to paper. It was to be another few decades, however, before the difference between colors was correctly understood, permitting a more precise distinction to be made between color mixtures. Colored light combines additively, to use the modern term. That is to say, the sum of light rays with varying spectral content, for example emanating from two lamps, will result in a new color. Unlike the ear, the eye (together with the brain) does not analyze the different incident wavelengths separately, but creates a new overall impression, i.e., a new color.

The additive mixture of red and green will, for example, result in yellow, and violet-blue together with green will give cyan blue. Two colors which additively neutralize each other, combining to form white, are called complementary colors. Experiments show that there are three such pairs: green and magenta, violet-blue and yellow, and red and cyan blue—to use the most exact possible descriptions.

Colored pigments have a very different effect from that of colored light. Whereas yellow light comprises light of a definite wavelength, the color of a yellow pigment is formed by the absorption of yellow's complementary color, which is violet-blue. The subtractive mixture of a yellow and a violet-blue pigment will not result in white, but black. This also applies for both remaining complementary color pairs. Not only red and cyan blue, but also green and magenta will result in a pigment which does not reflect light, and is thus black.

Here, we can point to a few distinctions which traditionally have been blurred, leading to confusion. In additive terms, mixing complementary colors results in white; subtractively, their mixture is black. Subtraction commences with all colors present (white) and ends up with only black. Addition begins without light (black), and is complete when all wavelengths are present (white). If red, green, and blue are regarded as the three additive primary colors (as they frequently are, because they deliver the largest palette of mixed colors), then for the same reason pigments which absorb red, green, and blue should be taken as the subtractive primary colors. In other words, the corresponding subtractive colors will be cyan blue, magenta, and yellow.

Of Sowerby's three original basic colors—red, yellow, and blue—we have replaced yellow with green, because at the time he presented his system, the English doctor and physicist Thomas Young (1773–1829) submitted his theory, later to be confirmed as correct, that the eye generates all colors by combining only three wavelengths. This Theory of Trichromatic Vision is based on the primary additive colors mentioned above: red, green, and blue. Young first arrived at his ideas for a trichromatic theory in 1801, when he explained that the eye cannot record each of the almost infinite number of colors separately, but most probably does this rather more sparingly: "Since it is hardly possible to believe that each light-sensitive point on the retina contains an infinite number of particles, which must all be in a position to oscillate with the respective wave in full agreement, it is therefore necessary to assume that this number is, for example, limited to the three main colors red, yellow, and blue."

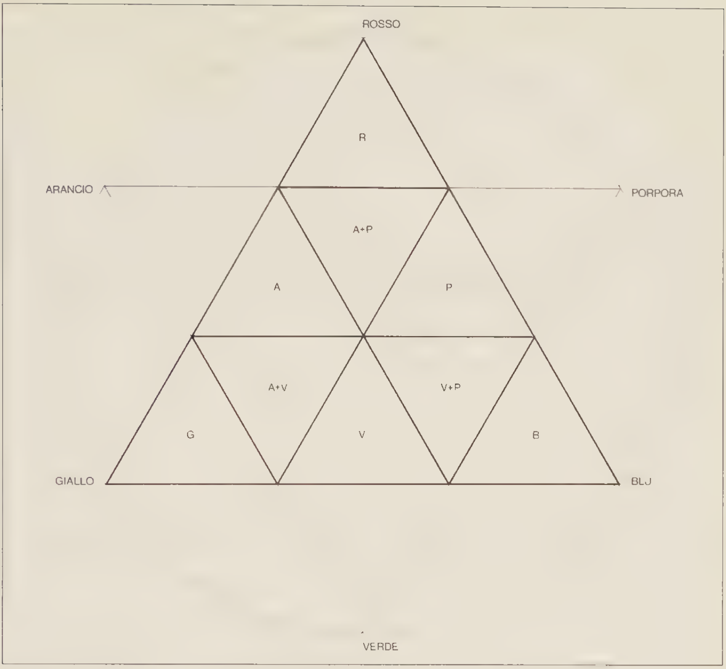
Yellow is not a misprint here. Young only later introduced, in 1807, the trio of colors with which the trichromatic theory is now linked, in his *Lectures on Natural Philosophy and Mechanical Arts.* "It is necessary," he wrote at that time, "to modify the assumption which I made in my last paper . . . and to replace red, yellow, and blue with red, green, and violet." Because the violet used by Young here appeared more like blue to his successors, for reasons of simplicity red, green, and blue are now associated with the Theory of Trichromatic Vision.

JOHANN WOLFGANG VON GOETHE

One hundred years after Newton, Johann Wolfgang von Goethe (1749–1832) examined the problems of color. By including all branches of the natural sciences, his *Theory of Colors* was intended to attain "a more complete unity of physical knowledge," but Goethe approached the subject primarily to gain some knowledge of colors "from the point of view of art." As he had written in a letter to Wilhelm von Humboldt in 1798, by embarking on his *Theory of Colors,* Goethe had also hoped to create a "history of the human spirit in miniature."

Goethe's first *Contributions to Optics* date from 1791, after he had experienced the difficulties encountered by contemporary artists with coloration and color harmony at first hand, on his journey through Italy. "Indeed, I heard tell of cold and of warm colors, and of colors which enhance one another, and suchlike," but everything turned "in an odd circle . . . of confusion."

Between 1790 and 1823, Goethe wrote some two thousand pages on the subject of colors, with most appearing between 1808 and 1823 under the title *Theory of Colors.* His system evolved from the elementary opposition of light and darkness (which was not a part of Newton's work). In his manuscript *On the Order of Colors and Their Relationship to Each Other,* Goethe established that only yellow and blue, as totally pure colors, "can be perceived by us, without being reminiscent of something else." Yellow, most easily compared with brightness ("next to light"), and blue,



most related to darkness ("next to blackness"), form the poles between which all other colors can be grouped.

When, in 1793, Goethe sketched his color circle, he did not place this basic pair of yellow *(gelb)*, and blue *(blau)* opposite each other, but extended them to a triangle together with a red *(rot)*, which was originally described as purple. He described "this red effect" as the "highest" of the series of colors leading from yellow to blue, and placed green *(grün)*, arising from the mixing of yellow and blue, opposite red. The circle is completed by an orange *(orange)* on the ascending left side, and on the right on the descending side by a blue-red *(purpur)*, which is often described as violet.

Next to the circle, in various small triangles, we have shown a few alternative possibilities for the layout of the

large triangle—similar to those of Joseph Albers in his *Interaction of Color* (1963)—in order to demonstrate an "expressive color accord."

The first case shows the series of primary colors (1.1), secondary colors (1.2), and tertiary colors (1.3). In the second case, we give an impression of what, with a "sensory-moral" point of view, Goethe explained as force (2.1), sanguinity (2.2), or melancholy (2.3). The third case emphasizes the three axes of the complementary colors: the red (3.1), the yellow (3.2), and the blue (3.3). Finally, we accentuate brightness or color value (4.1) and intensity or saturation (4.2).

Goethe referred to the part of his circle running from yellow to red as the plus side, and its continuation into blue as the minus side, and arrived at the following arrangement: yellow was associated with "effect, light, brightness, force, warmth, closeness, repulsion," and blue with "deprivation, shadow, darkness, weakness, cold, distance, attraction." It is suggested that Goethe's intention was mainly to ascertain the "sensual-moral" effect of individual colors "on the sense of the eye . . . and the eye's imparting on the mind." He understood colors mainly "as sensual qualities within the content of consciousness," and thus his analysis shifted into the area of psychology. The colors on the plus side "induce an exciting, lively, aspiring mood"; yellow has a "splendid and noble" effect, making a "warm and comfortable" impression. The colors on the minus side, however, "create an unsettled, weak, and yearning feeling," and blue itself "gives a feeling of coldness."

With his insight into the sensual-moral effect of colors, Goethe came nearer to his initial objective—to bring order to the more chaotic, aesthetic aspects of color. He placed

coloration within the separate categories of powerful, gentle, and radiant, and propounded that the powerful effect will arise if yellow, yellow-red, and purple predominate, with the gentle effect mainly being determined by blue and its neighbors. If "all colors are in equilibrium," a harmonious coloration will arise, which can produce radiance and also pleasantness. (The philosopher Ludwig Wittgenstein, by the way, notes in his *Remarks concerning colors,* "I doubt that Goethe's remarks about the character of the colors would be much use to a decorator, let alone a painter.")

Anyone comparing this short description of Goethe's *Theory of Colors* with Newton's preferred approach is immediately aware of two completely different attitudes to the same theme. But they do not really contradict each other—neither of the systems alone can completely cover all aspects of color. Their relationship can best be described as "complementary," in a deeper sense here than with colors. Newton's analysis of colors and Goethe's way of dealing with them were both, in some sense, correct theories. Each independently reproduced a valid aspect of our world, and was substantiated by the other. But Goethe was mistaken to conclude that Newton was misled, indeed "twice and three times over."

To bring more life into this idea of complementarity, let us compare what the English scientist and the German poet had to say about colors: What for Newton was simple—pure blue, for example, is light with one wavelength ("monochromatic light")—was complicated for Goethe, since pure blue must first of all be prepared by an extravagant means, and was therefore artificial. In contrast, white light was simple for Goethe, since it existed completely naturally, without effort. Newton, of course, saw in white light a

mixture of all colors. White light was not simple for him, but a combination.

Thus, what Goethe regarded as a unity, a whole—"das Schauen" or looking—disintegrated with Newton (and his successors) into many parts. For Newton, the act of viewing color commenced with a reaction in the eye, an explanation of which would require more detailed knowledge of the retina, the circuit of nerve cells, and the different stages that signals pass through on their way to the brain, and the regions in the brain which, through the generation of electrical signals, create vision.

The essential complementarity of the two color theories becomes evident when we consider the role of the subject—the human being. While Goethe, as a matter of course, viewed the subject as central, Newton totally omitted him from his description. Here, two complementary truths met. Goethe presented the direct truth of sensory perception as a counterbalance to the remote truth of Newton's science. Newton distanced himself from a conception of the world ("the pure human sense" as Goethe would have it), while Goethe expressively employed this notion to obtain clarity about the nature of colors. Something troublesome arises here, creating a certain tension in us. The opposite of one deep truth (here Newton's) is not something which is wrong, but is itself another deep truth (that of Goethe).

13 PHILIPP OTTO RUNGE

In 1810, the same year Goethe's *Theory of Colors,* with its color circle (Chapter 12) was published, the German painter Philipp Otto Runge presented his work on a *Color sphere.* As suggested by this title, Runge was interested in the "construction of the proportions of all mixtures of the colors with each other, and their complete affinity." Runge's sphere appeared in the year of his death—at only thirty-three. His color system, once described in an encyclopedia as "a blend of scientific-mathematical knowledge, mystical-magical combinations and symbolic interpretations," represented the sum total of his endeavors. Runge's color globe marked the temporary end to a development which had led from linear colors, via the two-dimensional color circles, to a spatial arrangement of colors in the form of a pyramid.

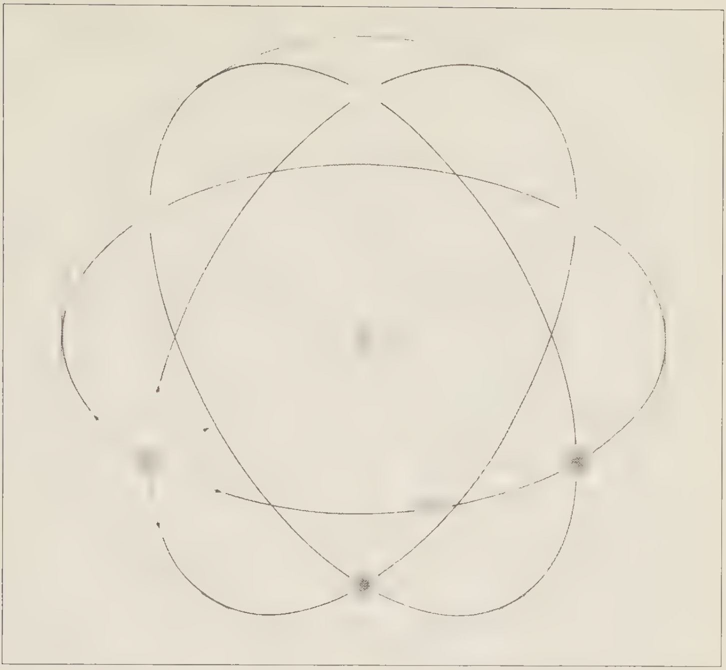
In the three basic colors of blue, red, and yellow (which to Runge, as a painter, were subtractive), he saw the "simple symbol of the Holy Trinity," as he wrote in a letter in 1803. To him, black and white were not mere colors, since "light is goodness, and darkness is evil."

The way to the sphere began with the color circle, which he drew in a letter to Goethe in 1806. Extracts from this letter were quoted in the didactic part of Goethe's color system: "It is apparent that only three colors exist, and these are yellow, red, and blue. If we take these at full strength, and if we imagine them arranged within a circle, then three transitional areas of orange, violet, and green will be formed. (I shall describe as orange everything which falls

between yellow and red, or which inclines toward red from yellow, or the reverse.) And in their middle position these are at their most brilliant and are the pure mixtures of colors." The three pure colors as well as the mixed colors terminate in the gray of the center. Gray, of course, can also be mixed from black and white.

In 1807, Runge shifted his attention to his model of a "globe," so that the relationship of the colors to white and black could be made comprehensible in a geometric form. The color sphere resulted in 1809. Its poles are black and white. The pure colors run along the equator with equal spacing. Each color placed on the surface of the sphere can move in five directions: toward the colors to the right or to the left, up toward white, down toward black, and inward to pass the gray of the center and continue on in the direction of its complementary color.

In the introduction to his color system, Runge complained that artists have been abandoned by scientists because scientists ignored those effects of color "not explained merely by the refraction of the ray of light." His objective was "to enquire into the mutual relationships of the given colors . . . in order that our impressions of their compositions and the altered appearances arising out of their mixtures can be deduced in a definite way, and can each time be reliably repeated when using our materials." He viewed colors as "a fixed, indeed independent phenomenon," and for this reason his investigations can be regarded "as fully remote from science, in the same way as colors themselves originate out of light." Runge selected the perfect symmetry of the sphere (and not the restricted symmetry of a double cone) because he believed that only then could "a completely neutral gray occur at its center." Only



in this way could the diametrically opposed colors on the surface of the sphere resolve themselves at its central point. Runge did not want his color sphere to be understood as "a product of art," but presented it as a "mathematical figure of various philosophical reflections."

Naturally, Runge knew of Lambert's pyramid, but he wanted to place the pure colors at the same distance from white and black, and thus decided on a round construction, which was also easier to associate with the divine order of the cosmos. Nevertheless, it was clear to him that his proposals could only be an imperfect representation of the ideal sphere, and he also must have been aware that the subtractive color mixture (this being the only possibility with his paints) did not produce the neutral, middle gray that was so vital to him. It could be inferred that Runge had in

mind something different from Lambert, who had mainly wanted to present a practical system as an aid to the mixing of colors. Runge did not want to record vividly the proportions of mixtures, but rather the harmonies of colors. He wanted to bring a sense of order to the totality of all possible colors, an order defined by a means other than language. As he stated in a letter to Goethe, "If we try to think of a bluish orange, a reddish green or a yellowish violet, it is like trying to imagine a southwesterly north wind." His sphere aimed at the creation of a genuine color system, an attempt not surpassed during his century.

14 CHARLES HAYTER

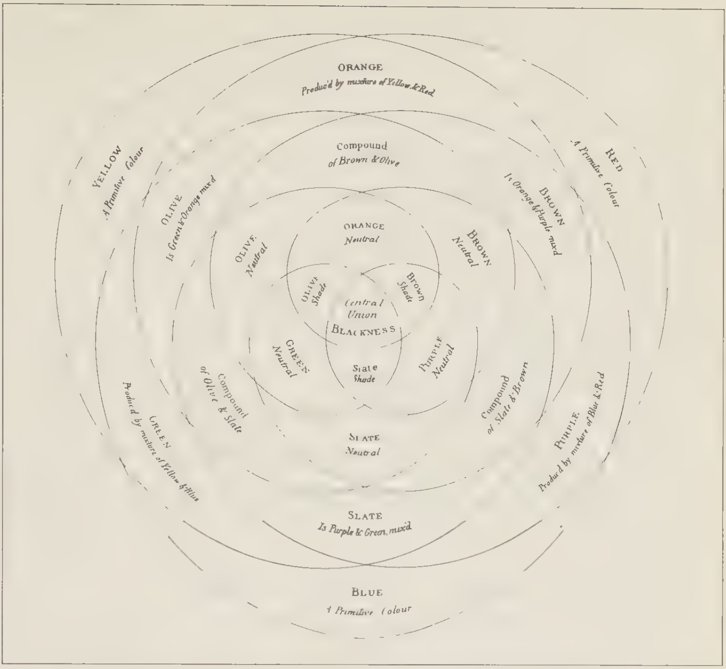
In 1826, the English architect and painter Charles Hayter (1761–1835) published a book in which he recommended Young's trichromatic theory as a practical basis for color reproduction. According to its subtitle, his *Compendium* of colors was intended to "show as examples the natural and inevitable consequences of simultaneous combination which result through gradual and systematic concentration of the three primary colors according to the recommendations of Leonardo da Vinci." Hayter claimed in his foreword that he already had a mental image of the diagrams and explanations—which he intended as a guide for painters—in 1813, and before that had never heard or seen anything of Moses Harris, who had touched upon much of what Hayter now expounded. We must here point out a contradiction: although Hayter, as a painter, wanted to provide a system for subtractive mixtures of pigment or dyes, he did not quote the appropriate forerunners of this line of thought, referring instead to Leonardo, Newton, and Young, who all thought more in terms of an additive, light-based system. Nevertheless, he saw with impressive clarity that a difference must be drawn "between the properties of such materials as give their colors in substances, suitable to the purposes of art, and the transient effects of LIGHT, which must not be considered as belonging to a system of mixing colors for the purpose of painting." Although Hayter neither generally nor rigorously analyzed this difference for the purposes of painting, he came to the

conclusion that "all transient or prismatic effects can be imitated with the Three Primitive Colors . . . but only in the same degree of comparison as white bears to LIGHT."

Hayter's basic triangle, comprising the three subtractive primary colors yellow, red, and blue, was of course by this time no longer an unknown construction, and we can recognize the black center as deriving from Moses Harris if nothing else. It is difficult to judge the originality of Hayter. We are already familiar with the Frenchman J. C. Le Blon. In a short paper completed prior to 1731, Le Blon was the first to introduce the group of yellow-red-blue—made famous by Goethe—as a subtractive trio of primary colors. His view about the fundamental character of his primary colors had been available in print since 1756, under the title *L'Art D'Imprimer Les Tableaux.* In it he provided instructions on the use of his basic colors for printing, weaving, and painting. Le Blon was proud of his construction, and pointedly mentioned that many of his colleagues did not believe that there were indeed such simple rules about art.

Hayter examined these concepts in greater detail (perhaps inventing new ones as well), while explaining his mixed colors. We can follow his diagram in three separate directions, starting at each primary color. First, from blue upward to orange, then from red to green, at the lower left; and finally from yellow down to purple, at the lower right.

The word "slate" is seen three times between blue and black in the center, which originally probably also appeared as gray. This slate color appears at three levels, as a mixture of purple and green, a neutral gray, and a shadowy gray. The lightness value increases again after the center is passed, with a mixture of brown and olive between a neutral and a yellow-red orange.



The red changes toward the center through three shades of brown. Thereafter it becomes green, in neutral, olive gray, and yellow-blue variants. Yellow gives rise to the olive color, which darkens via a neutral shade toward the center, continuing then as purple toward a blue-red.

The sketches show how we can move through the system, always crossing the center (black) in order to pass from one color to another. This interesting structure represents a spiral system in which both circular and radial paths coexist, and in which both singularities and pluralities can therefore be found.

Viewed in the context of scientific development, Hayter's system stemmed from a time when the controversy over the nature of light—which had persisted since Newton—seemed finally to have been resolved. On the one

hand, Thomas Young, whom we have already discussed, had proved that light rays can interfere with each other; under controlled conditions, light added to light can result in darkness. This property of interference applies only to wave formations, and not to particles. In the 1820s, the Frenchman A. J. Fresnel was also able to demonstrate that all optical phenomena can be understood if light is conceived as an oscillation in a (hypothetical) medium, with the direction of oscillation being vertical to the direction of propagation (transverse). In 1821, the German physicist J. von Fraunhofer actually succeeded in measuring the length of the waves which made up light. He used a diamond to scratch fine, closely spaced, parallel, and vertical lines on a sheet of glass, and then studied the "deflection" of light through this so-called "diffraction grating." By 1835 at the latest, the physicist F. M. Schwerd was able to take exact measurements of the visible spectrum with the aid of such a diffraction grating, and show that red light has a longer wavelength than blue light, and that yellow and blue light lie in the middle of the spectrum. (The nanometer—10^{-9} meters, or 10^{-7} centimeters—has now become the standard unit of measurement, with the wavelength of the visible spectrum lying within a range of a few hundred nanometers.)

Thus we can see that the first half of the 19th century was the heyday of wave theory. For the first time, it seemed that science could rest assured that something about the nature of light had been understood. But fundamental problems with regard to our conception of waves were to re-emerge at the beginning of this century, and still are with us to this day.

15 MICHEL EUGENE CHEVREUL

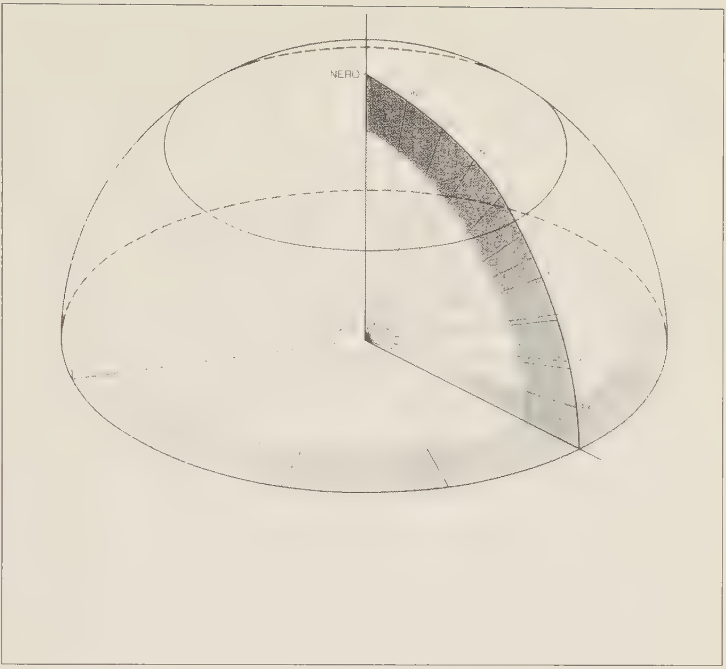
While he had no interest in understanding or dealing with colors in the same way as artists, probably no other chemist has influenced the development of art as much as the Frenchman Michel Eugène Chevreul (1786–1889). In 1824 he was appointed director of Paris's Manufacture nationale des Gobelins, the renowned tapestry manufacturer. There, he concentrated on the problems of dyeing, and therefore on the dyes themselves. Chevreul supervised the preparation of these dyes, and it became clear to him that the main problems had nothing to do with chemistry, but in fact were related to optics. Frequently a color failed to achieve the desired effect, not because of the pigments, but due to the visual influence of neighboring color tones. Chevreul decided to investigate the matter scientifically, and in 1839 published his *De la loi du contrast simultané des couleurs,* a comprehensive attempt to explain on a systematic basis how we see colors. The work dealt with the so-called "simultaneous contrast" of colors, and contained Chevreul's famous law: "Two adjacent colors, when seen by the eye, will appear as dissimilar as possible."

His work, while impractical and incomplete, nonetheless influenced the views of both Eugène Delacroix (1798–1863) and Georges Seurat (1859–1891) on colors and the way they were used. Chevreul also help guide the theories behind Impressionism, Neoimpressionism, and

Orphism. A chief exponent of this last style, Robert Delaunay (1885–1941), actually used colored "simultaneous discs" in his paintings.

Leonardo da Vinci is the first person we know to have noticed that juxtaposed colors influence each other. But it was Goethe who first specifically drew attention to these associated contrasts, and described them with such emphasis that people actually became aware of them. Someone looking at the same red, first on a yellow background and then on violet, will have two different impressions: in the first case of a darker red, and in the second, an orange red. Chevreul established two different ways in which simultaneous contrast occurred, referring to changes in color intensity and "optical composition." Today, we know that there are actually three attributes which can be displaced due to the influence of a neighboring color. These three characteristics correspond to the three dimensions of a "solid" color system (i.e. a sphere or pyramid) and are named brightness (or white-black value), hue, and saturation (or chroma). One and the same color will give a lighter effect against a dark background and a darker effect against a light background. A pure red will have a redder effect on a yellow background and a yellower effect on a reddish background. And a dull grayish red will have a more colorful effect (less gray) on a neutral gray background than on a colored background.

This simultaneous interaction of colors can be easily understood or interpreted using the color circle or the color sphere if we assume that the background color will repel the color of the color field observed. But of course it is our perception that actually does this. It seems reasonable to assume that our eyes and brain will try to perceive any differences occurring in nature as clearly as possible, and this



explanation agrees with the observed displacement represented by the color circle.

This is the first time that we have considered the active role of the brain in the formation of colors, so we should remind ourselves once more that colors are also effects created in the world inside our heads.

Let us return to Chevreul, who in his 1839 work demonstrated that a color will impart its own complementary tinge to an adjacent hue. As a result, opposing complementary colors, like orange and blue, will intensify when placed side by side, while non-complementary colors will appear "contaminated," for example a yellow next to a green acquires a tinge of violet.

The laws of color contrast occupied Chevreul during his search for an organization of colors suitable for the

manufacture of textiles. For this purpose, he designed the 72-segment color circle shown here. The circle defines the color hues on the basis of the various changes which a color undergoes in the direction of white (higher value) or black (lower value). According to Chevreul, there are ten possible steps. It is worth noting that in his color circle, Chevreul arranged each of the saturated colors on a varying radius within its associated segment. Pure yellow lies nearer to the center than pure blue. Pure red lies at point 15 on the scale. By this means, the color hues for the different pigments are given more appropriate positions than in preceding systems.

In Chevreul's color circle we find three secondary colors (the primary mixtures orange, green, and violet) alongside the three subtractive primary colors (red, yellow, and blue), as well as six secondary mixtures. The segments arising in this way are thus each divided into six zones, and each radius is divided into 20 sections in the form of a ladder, in order to specify the different brilliance or lightness values.

With his hemisphere, Chevreul attempted to provide us with a spatial representation of the colors appearing in his two-dimensional color circle. The black axis of the hemisphere thus becomes a pointer, pivoting to select the different levels on a scale. The numbering will then specify the proportions of a color; for example 9B/1C will mean that 9/10 black and 1/10 of the corresponding (color) hue are present.

Chevreul was convinced that the many different color hues and their harmony could be defined in terms of relationships between numbers, and he wanted his color system to become a practical instrument available to all artists using colored materials. Although his harmony systems, which he described as "Harmonie d'analogues"

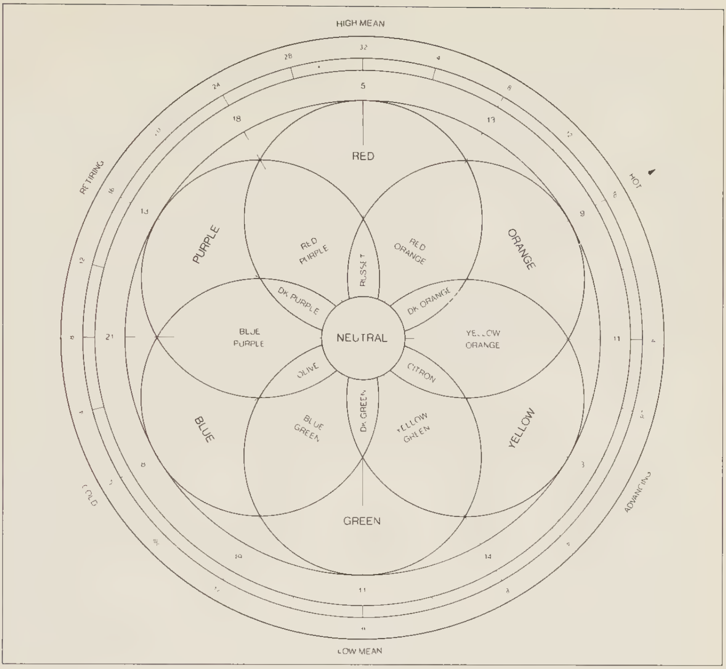
(harmony of analogy) and “Harmonie de constraste” (harmony of contrasts), had great influence, he was unable to discover an overarching law of color harmony. And indeed, it simply does not exist.

16 GEORGE FIELD

George Field (1777–1854) was a chemist who was occupied not only with the practical aspects of pigments and dyes, but also with the theory of their harmonic relationship. His first work, "Chromatics," an essay written in 1817 on the "Analogy and Harmony of Colors," used the three subtractive primary colors red, yellow, and blue, and was concerned with the arrangement of a color harmony as an "aesthetic analogy" of the musical harmony system. In his essay, Field describes a "metrochrome," equivalent to the musical metronome, consisting of three calibrated wedge-shaped glass vessels filled with red, yellow, and blue liquids. For our purposes, it is enough to appreciate the reason for so many numbers in his system, without needing to understand each one individually.

His *Chromatography* (1835)—perhaps the title sounds like a scientific method—a second discourse on colors and pigments, featured the "color compass" shown. His compilation *A Grammar of Coloring* followed, chiefly intended to provide artists information on the origin, composition, and properties of pigments, dyes, and paints.

In these three works, Field established a link with the works of Jacques Christophe Le Blon, who in 1730 had put forward a palette of the three "primitive" colors red, yellow, and blue, and the three mixed colors orange, green, and purple (thus taking up a position opposed to Newton). Field declared the six colors of his circle to be primary colors, from which the secondary and tertiary colors arise



through gradual change. While Field characterized his secondary colors simply by using double names, and saw the three tertiary colors as dark (dk) variations of the mixed colors already mentioned, three special names appear in his color compass: the mixture of purple, blue, and green is called "olive"; the mixture of green, yellow, and orange is called "citron"; and that of orange, red, and purple is called "russet."

Different meanings or connotations, marked along the circumference of the circle, are assigned to the colors: hot and cold stand opposite one another, as do advancing and retiring, as well as a high mean versus a low mean value. Both the smaller sketches show us how we can pass through the main circle—from outer to inner, from bright to dark, and from concave to convex.

Perhaps at this point a brief explanation is needed of the link between colors and sounds which George Field sought to establish. Attempts to relate light and music date back to ancient times. Athanasius Kircher (Chapter 3) was the most recent to reiterate that everything visible to the eye can also be made audible for the ear. It was not until 1760, however, that a developed system for color music was presented by the Frenchman Louis-Bertrand Castel. He made the following, fairly arbitrary allocation: C was expressed by blue, and C sharp by blue-green, D by green, D sharp by yellow-green, E by yellow, F by yellow-orange, F sharp by orange, G by red and so forth to B, which is represented by indigo. From the triad blue (keynote C)-yellow (third E)-red (fifth G), he arrived at a twelve-step chromatic color music scale via different intermediate levels. In 1844, Field suggested an alternative allocation, leaving C with blue, but bringing D to purple, E to red, F to orange, G to yellow, A to yellow-green, and B to green. His *Analogous Scale of Sounds and Colors* was based on the triad blue-red-yellow.

Music and colors most probably are related, deep down, but their connection is not easily established—a color piano certainly overwhelms our imagination—even if, in their wave motion, sound and visual stimulus seem to share a common physical basis. In fact, sound and light waves are not comparable, indeed they are about as different as any two things could ever be. The principal difference lies in their respective media of propagation. Waves can only exist when a carrier—a medium—is available. Ocean waves are carried by water, waves of music and sounds are carried by air. This is demonstrated by the experiment in which an alarm clock is placed in a glass bell and the air is pumped out. The ringing clock can be seen rattling, but there is

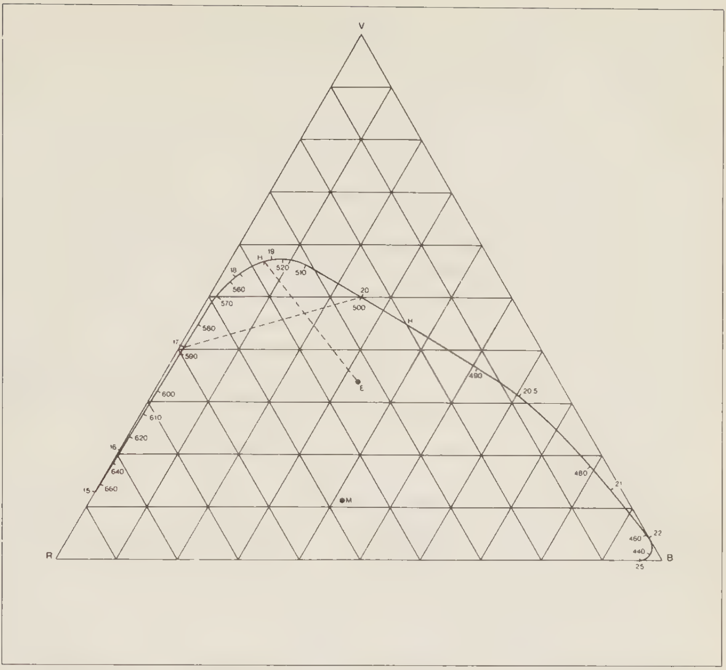
silence, because the waves of sound no longer have a propagation medium. While sound waves capitulate to the relative vacuum of the bell, light waves manage to pass through it with ease—after all, we can still actually see the alarm clock. Air is not light's medium. Indeed, if light waves could not cross the vast emptiness of the universe, we would see no stars. Thus around the time of Field's death, the scientific world was confronted by a great mystery, the exact nature of the medium in which light waves are carried. Physicists had already named this mysterious substance "ether." But how could something which had to be harder than steel to make possible the minute wavelengths which light was known to possess be at the same time so imperceptible that the planets could orbit within it undisturbed? An initial solution to this great problem came after 1860, in the work of the Scottish physicist James Clerk Maxwell, who not only profoundly influenced the history of light, but also the history of colors.

17
JAMES CLERCK MAXWELL

The year 1859 is one of the greatest in the history of science. Charles Darwin expounded his ideas on the origin of species in that year, clearing the way for the theory of evolution. And the physicist James Clerk Maxwell (1831–1879) published his *Kinetic Theory of Gases,* in which he introduced a statistical account of the molecular motions and their mathematical treatment, renowned today as Maxwellian distribution, which contributed to our fundamental knowledge of physics.

In the same year, Maxwell, then 28 years old, also presented his *Theory of Color Vision,* acknowledged as the origin of quantitative color measurement (colorimetry). In this work, he demonstrated that all colors arise from mixtures of three spectral colors—for example from red (R), green (here abbreviated to V), and blue (B)—using the assumption that the light stimuli can be both added and subtracted. He allocated each of the three principal colors to the vertex of a triangle, and in it we have placed a curve of the spectral colors of the rainbow along with some technical data. A line of this type will reappear later (Chapter 35). We note this to show that all related insights go back to Maxwell, who with his triangle introduced the first two-dimensional color system based on psychophysical measurements.

It is hard to explain to the outside observer just how famous Maxwell is among physicists. In addition to the Maxwellian distribution already mentioned, his name is



also associated with the four so-called field equations which explain how light propagates, and which point to the existence of electromagnetic waves. We make use of the reception of these waves today, for example when we listen to the radio or watch television. Maxwell showed that light waves can be understood as oscillating electrical and magnetic fields, and he explained how it is possible for light waves to travel across the vast emptiness of the universe and reveal the stars to us.

Before coming closer to discovering the nature of light, Maxwell had directed his efforts toward achieving a more exact access to colors. As a result of his contribution, physics and the measurement of light and color re-emerge in post-Newtonian history, Maxwell's triangle being in part an attempt to improve on Newton's methods of mixing

light. In the preceding decade physicists had learned to determine wavelengths in the region of 10^{-7} meters with the aid of diffraction gratings. As we have seen, wavelengths are today expressed in terms of nanometers, with the wavelengths of visible light known to lie in a range between 760 nm. for red and 380 nm. for blue, green being at approximately 550 nm. (These values are indicated along the curve.)

Maxwell's observations were based on propositions made by Thomas Young (see Chapters 11 and 14), who had already noted that no more than three colors of the spectrum were required to create all others. When Young submitted his trichromatic theory, many artists had long since known that one could mix all color shades by using three primary pigments. Physicists, however, were still influenced by Newton's claim that the seven colors emanating from a prism were elementary (therefore not able to be made by mixing).

Young's theory of three photoreceptors gained in plausibility when, in 1855, George Wilson of Edinburgh presented the first statistical analysis of color blindness. In an appendix to it, Maxwell showed that the observations were understandable if one assumed that affected individuals had either one or two ineffective receptors.

Maxwell had begun his own experiments on color mixing in Edinburgh, in the laboratory of J. D. Forbes, who himself worked with rapidly rotating color discs. With them, Forbes wanted to mix the spectral colors to create gray. But he was unsuccessful in his attempts to obtain gray from red, yellow, and blue. He soon noted the reason—namely, under these circumstances blue and yellow do not result in green, but rather a kind of pink. As a result, Maxwell decided on the primary colors of red (R),

green (V for verde), and blue (B), and so we encounter them again in his triangle. (He did clearly stress, however, that any other trio of colors can be selected that combine to give white.)

In his experiments on the measurement of color, Maxwell engaged test subjects to judge how the color of a sample corresponded to a mixture of the three basic colors. Today, the test subjects themselves are allowed to change the mixture of red, green, and blue (aided by standardized light sources) until the impression of the color corresponds to that of the sample (a "color match"). The proportions of each mixture can be recorded using three numbers, identified as R, V, and B, known since Maxwell's time as "tristimulus values."

Maxwell then became aware that the brilliance of a multicolored surface is relatively insensitive to changes in brightness, and was able to eliminate this completely as a determining factor by introducing new "normalized" parameters r, v, and b. To obtain these he simply divided each of the tristimulus values by the total: $r=R/(R+V+B)$, $v=V/(R+V+B)$, and $b=B/(R+V+B)$. These new color coordinates fulfilled a very useful, simple condition completely (their sum is always one ($r+v+b=1$). This permits all their possible combinations to be represented as points within an equilateral triangle with red, green, and blue at the vertices—in fact, Maxwell's triangle. A few examples can be seen in the series shown on the left. The white neutral point is found in the center of the construction.

Since their tristimulus values, that is, their color coordinates, add up to one, the mixtures of two colors can be readily predicted. All possible combinations of any two colors will lie on a straight line connecting their positions

in the triangle. Of course, Newton's circle had already specified the results of color mixing. But Maxwell's achievement was that the geometrical relationship and spacing between the colors in his triangle had a precise meaning, based on psychophysical measurements.

In his color mixing experiments, Maxwell could demonstrate that Newton's circle of seven colors, with white as a middle point, implicitly satisfied the trichromatic theory since it is equivalent to a model which allocates a point within a three-dimensional space to each color. As he entered the experimental results into his color triangle, he located the point for white. Relative to this point, Maxwell was able to specify three new parameters—much like Helmholtz (Chapter 18) which characterize a color: the "hue," the "tint," and the "shade." Maxwell also readily demonstrated graphically a link between these variables and the portrayal of colors as the sum of three primaries.

The limitations of this triangle, incidentally, soon became apparent. Its values are based on comparisons of pigments, but the light of spectral colors can be much more intense. For example, anyone seeking the location of saturated yellow will see that it must lie outside of the line between V and R. If all the spectral colors, together with the purple hues, are to be recorded in Maxwell's diagram, then his triangle must either be extended or reconstructed.

HERMANN VON HELMHOLTZ

Hermann von Helmholtz (1821–1894) was the absolute leader in the natural sciences of his day, dominating with his incisive intelligence. His first great achievement, in 1847 at the age of twenty-six, was to formulate the principle of the conservation of energy. Helmholtz also demonstrated great practical talent, for example, in inventing the opthalmascope. His *Theory of Sound Sensitivity* (1862) both proposed a theory for the combination of tones and analyzed the timbre of musical instruments, even providing the outlines of a theory of harmony.

His famous *Manual of Psychological Optics* was published between 1856 and 1867, while the English translation first appeared sixty years later, to world acclaim. Here, Helmholtz introduced the three variables which are still used to characterize a color: hue, saturation, and brightness. He was the first to demonstrate unequivocally that the colors which Newton had seen in his spectrum (Chapter 6) are different from reflected colors applied to a white base using pigments. The spectral colors shine more intensely, and possess greater saturation, because they are mixed additively, while pigments are mixed subtractively. A different set of rules governs their combination in the two cases.

Helmholtz's investigations were constantly guided by the analogy of the eye and the ear. The three variables of color sensation mentioned above were chosen to correspond to

the three parameters of sound: volume, pitch, and timbre. The only difference between acoustic phenomena and color perception was that the eye cannot differentiate between the components of a mixed color, while the ear could easily identify the separate elements of a complicated sound. As Helmholtz put it in 1857, "The eye cannot separate combined colors from each other; it sees them as an unresolvable, simple sensation of one mixed color. It is therefore of no consequence to the eye whether basic colors of either simple or complicated conditions of oscillation are combined in a mixed color. There is no harmony in the same sense as with the ear; there is no music."

Following Thomas Young (see page 52), Helmholtz also advocated a three-color system, and demonstrated that every color could be composed as a mixture of three basic colors, for example using red, green, and blue-violet as the so-called "simple colors." In his manual, the great physiologist then made several proposals for the arrangement of these pure colors—thus covering the entire spectrum. He also attempted to intercede—in a rather casual but vivid formulation—between Newton and Maxwell. For Helmholtz, Maxwell's triangle was too small to accommodate the saturated spectral colors, and Newton's circle did not explicitly refer back to the trichromatic theory, with its profound implications.

Helmoltz first arranged the spectral colors on a curved line to achieve a better understanding of their mixtures. He imagined a kind of force field of colors—the color field—with white in the middle, corresponding to Newton's gravitational center. Helmholtz noticed that to obtain white, he did not require equal quantities of violet-blue and yellow, for example. He thus arranged his colors in such a way that

complementary colors required in greater proportions were given greater "leverage."

Newton's circle formed the basis for a second construction by Helmholtz, in which two triangles were plotted, after omitting the part which intersects the line between red (R) and violet (V). This truncation is possible without detriment only because the two colors concerned mark both the ends of the spectrum. (In Chapter 37, we will encounter this line once again as purple.) In the figure, we are left with two triangles whose corners bear the two possible combinations of three basic colors. Young had wavered between these two combinations at the beginning of the 19th century. The triangle with the violet, red, and green (VRG) corners thus contains all the colors which are formed from mixing violet, red, and green; likewise for the

red, yellow, and cyan blue cornered triangle (RYC). It is apparent from the figure—and also from Maxwell's triangle—that not all colors can be recorded in this way, in fact that a large portion of the color circle remains absent.

There were, of course, no doubts about the trichromatic theory in Helmholtz's time, and this encouraged the belief that there really must be an ideal triangle with a place for all the mixed colors of the spectrum. With another construction Helmholtz returned to that first curve of simple colors, which he had drawn assuming that quantities of light of varying color are the same when, at set intensities, they appear equally bright to the eye. Starting with a base of the pure colors red and violet, without further explanation, Helmholtz moved the point representing our perception of pure green to A, to form a triangle AVR which now was supposed to contain all sensations of color.

Later, Helmholtz drew the conclusion that the pure red and pure violet of the spectrum do not exist as a simple sensation of a fundamental color, so the lower line had to be displaced to the values V1 and R1. The colors which can be directly attained by means of light entering a normally seeing eye will then lie on the closed curve V/ICGrGR/ (the abbreviations refer to indigo, cyan blue, green, and yellow). The triangle also contains colors located at a greater distance from white, and more saturated than all standard colors.

Both Helmholtz and Maxwell concentrated on finding the most suitable diagram to explain the observed facts with regard to color mixtures. Because the trichromatic theory was available and accepted, their attention was turned toward the geometry of the triangle, without any consideration of the phenomenological aspects.

The question concerning the position of the spectral

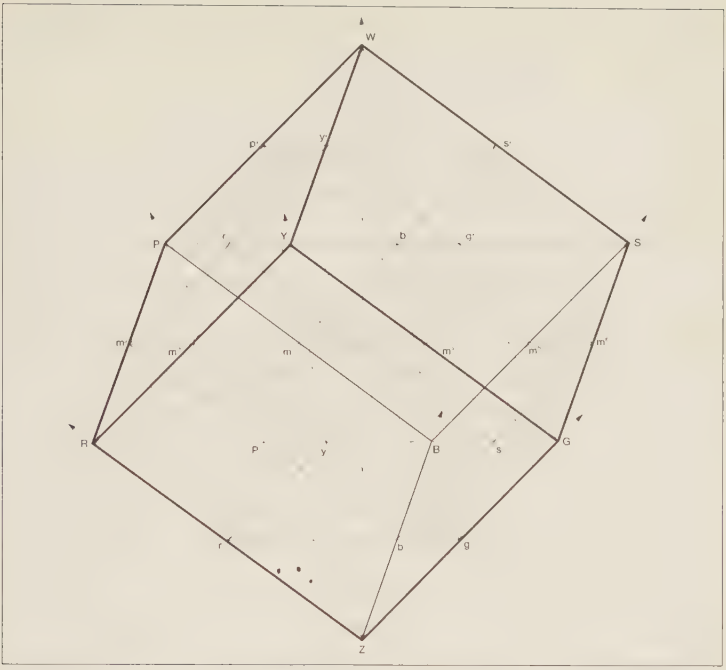
colors in each triangle was only finally resolved at the end of the 19th century, when A. König and C. Dieterici examined "the basic sensations in normal and anomalous color systems and the distribution of their intensity in the spectrum" and specified the course of the line which we have plotted in Maxwell's triangle. This is only scientifically correct if we imagine here an ideal triangle whose colors possess greater saturation than the spectral colors. (E marks the point of equal energy, and this can also be interpreted as white.) The results of the spectral mixtures illustrate how Newton had simplified matters when he assumed that the saturation of mixed colors will be less if, within the sequence of colors, their components are located further apart.

The work of König and Dieterici appeared in the German journal *Zeitschrift für Psychologie* in 1892, marking the shift in the pre-eminence of color theory to contemporary physicists. But the power of perception would in the end prevail; without it, the technical game with colors would remain all too trapped in geometric constructions, even when practiced by a genius, like Helmoltz or Maxwell.

19 WILLIAM BENSON

In Maxwell's triangle, three slightly darker primary colors are located in the middle of the sides opposite three brighter colors. These are then reached by moving from each corner straight through the white center point. Blue-green (cyan) lies opposite the red corner, with purple (magenta) opposite green, and yellow opposite blue. If we want to create a spatial color system from this triangle, we can follow the method of the English architect William Benson. In 1868, he proposed the first of his many color cubes. He regarded this arrangement as the "Natural system of colors," the title of Chapter 7 of his *Principles of the Science of Color.* After citing the preliminary work of Mayer, Runge, and Chevreul, Benson proceeded to justify his own preference for an alternative geometry:

"In order to use the normal methods of geometrical representation of all combinations which can be formed from three independent variables, a point must be chosen which represents zero or black, the absence of all light, and three lines must be drawn from it at right angles to each other, along which and on all parallel coordinates the colors red, green, and blue shall increase in intensity, commencing at zero. The intensities of red, green, and blue, which collectively give white, shall be the same, and are therefore represented by equal distancing along the three right-angled coordinates. The end points of these three lines will thus be the places for the full red, the full green, and the full blue, while the lines themselves contain the shades of these three



colors toward black. . . . The corner of the cube opposite the black would be the full white, and the corners lying opposite red, green, and blue would be sea green, pink, and yellow. The central point would be a medium gray." The unexpected priority of pink over purple is probably related to its brightness.

Benson's cube contains 13 main axes, which he divided into three groups (distinguishing contrasts, shades, and harmonies). There are three axes connecting the central points of opposing sides and, because only one of the primary colors changes along them, these are termed "primary axes." In the figure they are shown as solid lines (together with the lines parallel to them). There are six more axes connecting the midpoints of opposing edges. Going along these, two primary colors will change, so Benson referred

to them as "secondary axes." Both they and their corresponding parallels are shown by dashed lines. Finally, the four internal diagonal axes which join opposing corners are named "tertiary axes," since all three primary colors change along them. These are also shown with dashed lines. Benson gave exact color names to all the many points at intersections, but we will only mention those along the line from m^1 to m^6: m^1 is pink, m^2 is yellow-red, m^3 is pink-blue, m^4 is yellow-green, m^5 is sea green, and m^6 is sea green-green.

We can go back and forth through this cube along many routes, and it can be divided into many levels. To illustrate the potential diversity of colors in the cube, we have plotted a few main positions. The cube represents various horizontal projections that are obtained going from white to black. The inversion of the triangles is here a geometric phenomenon.

William Benson's system was an attempt to deal with both additive and subtractive mixing of colors. But as a color system, a cube will always be confronted with the basic problem that it does not fully allow for the significance of brightness and thus locates the color hues inaccurately.

20 WILHELM VON BEZOLD

Wilhelm von Bezold (1837–1907) was Professor of Meteorology in Munich and Director of the Prussian Meteorological Institute. His main interest as a scientist was the physics of the atmosphere, and he contributed much to the theory of electrical storms. His uncle Gustav was a prominent art historian, and this may well have been instrumental to the appearance, in 1874, of the *Farbenlehre im Hinblick auf Kunst und Kunstgewerbe* (Color Primer for Art and Design), in which the younger Bezold introduced a color system in the form of a cone. Although reminiscent of Lambert's pyramid, this cone is conceived differently—being more similar to Chevreul's hemisphere.

Bezold noted, "In such a color cone, it is possible . . . to accommodate absolutely all conceivable colors, which means all color hues that our eyes are capable of perceiving. On its outer surface, the cone contains only completely saturated colors, of various levels of brightness. . . . If such a cone is actually to be manufactured with the aid of dyestuffs, the outer surface, containing the spectral colors, in other words the completely pure colors, can still only be imagined, since even the outer pigments available are far from complete purity."

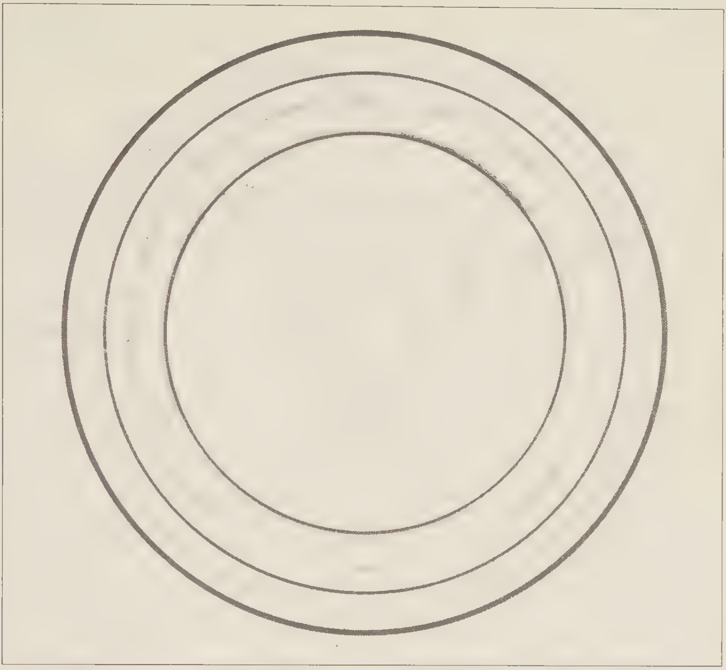
Bezold's intention was to create a color system based directly on perception. But he was not the first to attempt this. The painter Johann Christoph Frisch, in Berlin, is probably entitled to the honor. In 1788, Frisch had introduced an asymmetrical construction, proposing a color circle with eight different-sized segments, allowing

for the eye's recognition of a greater distance between blue and red, and between blue and yellow, than between yellow and red. But Frisch's attempt did not find much response, and it was another one hundred years before Bezold made his similar proposal.

Bezold's color cone has white at the center of a circle which forms its base. The colors darken toward the tip of the cone, where black is reached. He derived the circle from his experience that, "if the purple colors are placed between violet and red, it is in fact possible to accommodate all hues in a recirculating series. They can therefore also be distributed along a closed line, most easily around the circumference of a circle, and thus are given material form."

(In the second edition of Bezold's color theory, which appeared in 1921—almost half a century later—the publisher, W. Seitz, undertook some radical changes. Bezold's cone, for example, was replaced with William Ostwald's double cone, which we will describe later [Chapter 30].)

Bezold introduced a special color circle. He regarded this circle as a section, "a portion of the true color chart which approaches the shape of a triangle, in the corners of which can be found the colors red, green, and blue-violet." So he was strongly oriented toward the three primary colors of blue, green, and red, which Herman von Helmholtz (Chapter 18) and James Clerk Maxwell (Chapter 17) had been able to justify scientifically and popularize in their three-color theories. This had led to Bezold's selection of a triangle as the true color chart. In his 1874 preface, he acknowledged his two predecessors and their achievements, reminding us that Helmholtz was the first to recognize the difference between the additive mixing of light rays and the subtractive mixing of dyes, and that we have Maxwell to



thank for the laws of "true color mixing, established with the aid of convincing experiments." It was only after their investigations, Bezold continued, that the physical and psychological aspects of the theory of color assumed sufficient form for it "to be able to serve as a basis for practical, aesthetic enquiry." He went on to write that it was now time to try—and here Bezold had his own work in mind—"to organize the theory of the formation of color in a similar way and on a firm basis, and to place it as a companion of equal stature at the side of both other sciences"—meaning anatomy and geometry, both of which are significant to art.

His own color circle was therefore "constructed with the aid of the triangle, so it is to be seen as a detail of this triangle, or an enlargement of the small circle drawn in the triangle. Graduations arranged around the circumference

give the numbers of wave oscillations (frequencies), in such a way that in going to the next graduation, this color has 10 billion more oscillations per second than its predecessor . . . . The mere distribution of these graduations, which harbor within them a palpable form of the rigorously mathematical law of mixing, points to the peculiar relationship between the colors red, green, and blue."

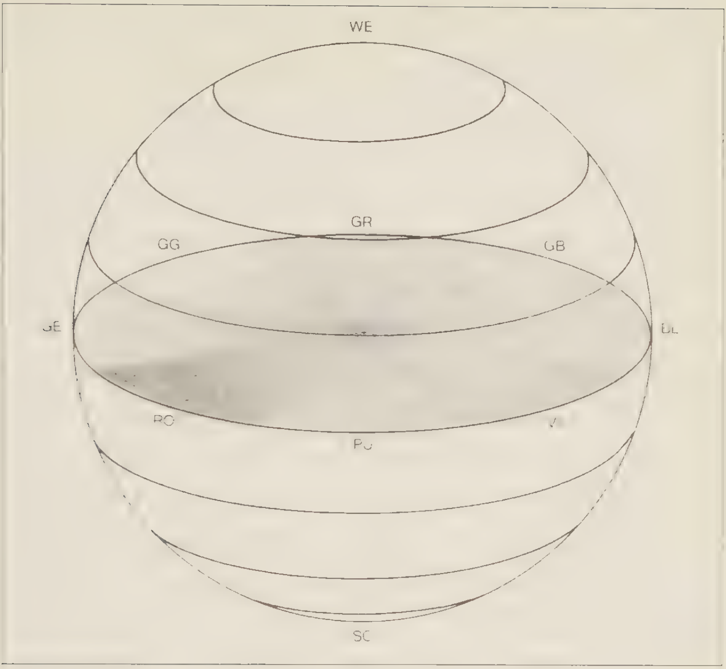
In spite of the attention he paid to science and scientific quantification, Bezold was primarily concerned with art and design, and sought with his circle to assist painters and dyers. Even if the most exacting experiments and a sense of order suggest that "on one and the same course of the circle's circumference an approximately equal number of barely distinguishable hues are located next to one another, the impression remains that the hue in the area of blue and green changes at a much slower rate than in the area of purple and violet." Consequently he attempted "to divide the circle into color groups in such a way that the character of the neighboring groups appear to the eye as being of equal difference." The individual hues going toward green are purple, carmine, vermilion, orange, yellow, yellowish green, green, bluish green, turquoise blue, ultramarine, bluish violet, and purplish violet, with numerous "complementary colors" being placed opposite green, the largest sector. The letters placed along the inner circumference represent musical notes, and they are part of an attempt to refute the theory of "chromatic equivalents," which can be traced back to George Field (Chapter 16). We must leave both these aspects untouched, except to note that Bezold took great pains in his search for a harmony of colors, seeking harmonic triads through the construction of equilateral triangles around the white center of his color circle. We

show one triangle, which links blue-violet and vermilion to green. Its tip does not reach into the green sector, illustrating a basic failing of systems which assume that an integration of colorimetry into a planar geometry is possible. Color systems must be three-dimensional, but it is not necessary for their structure to be graphically simple; simplicity was first achieved by a system proposed by the American painter A. H. Munsell (Chapter 29) at the beginning of the 20th century. Bezold was indeed unable to present a comprehensive color system—he overemphasized the blue and violet hues. But his name is kept alive in modern perceptual physiology by the "Bezold-Brücke phenomenon." Here he observed electrical lamps through colored filters and noted that the brightest point of the lamp, when seen for example through a red filter, was discolored yellow, and was discolored green when seen through a blue-green filter. The colors we see are thus dependent, at high values, on the intensity of the light. This displacement of perception is explained today by assuming that at the point of greatest light intensity—the brightest point—the photoreceptor cells in the eye, which are maximally excited, become saturated and thus contribute relatively less to our perception of colors.

Brücke, incidentally, had previously attempted to formulate the psychology of colors in an aesthetic system. In his book, Bezold ventured a second attempt—to him all the more essential since Goethe's *Theory of Colors*, in his opinion, "had no lasting influence on the development of science, and had long been the object of superb disproof." A hundred years ago it was still possible to write in this way without anyone objecting. In the meantime, scientists have come around to understand such matters more fully.

31 WILHELM WUNDT

Psychology emerged as a new science toward the end of the 19th century. One of its early pioneers, Wilhelm Wundt (1832–1920), helped establish the experimental branch of psychology and secure it as an empirical science. He had studied physiology and philosophy, and, in the course of his life as a researcher, laid the foundations for *Physiological Psychology*—the title of his twin-volume textbook dating from 1887, which is still successfully marketed as a standard work. Wundt was able to return to a form of psychophysics, which had been mainly developed by Gustav Fechner (1801–1887) to investigate the relationships between the measurable phenomena of the physical world and their experienced (psychic) image, i.e. perception. The fact that smaller differences in brightness can be perceived when it is dark led Fechner to venture the general conclusion that the visible increase in stimulation (increase in brightness) maintained a constant relationship to the basic stimulus (brightness itself). Fechner further envisaged that the effect of this relationship was continuous, also applying to the tiniest ("infinitesimal") changes. He thus derived Fechner's Law, still well known, which defines the relationship between differences in the sensation of brightness on the one hand, and the light intensity or corresponding differences between color hues on the other. (To be more exact, we must talk of the "Fechner-Weber Law," which states that an



arithmetic increase in perceptions requires a geometrical increase in the stimuli.)

Wundt was enthusiastic about Fechner's law and attempted to extend it beyond a link between stimulus and reaction, to envisage a relationship between stimulus and sensation, but this was never convincingly formulated. Fechner's relationship is not, in fact, a law in the truest sense of the word, being at best an approximation of the actual circumstances. And after the initial enthusiasm, psychophysics has become something of a peripheral science.

Wundt was involved extensively with colors, and actually designed two related systems, both conceived from the principle of opposition (derivable from the polar attributes of the empirical world, such as excitement and calm, or well-being and pain). In addition to an initial sphere-shaped

system dating from 1874, which was oriented toward the Forsius diagram (Chapter 1), Wundt envisaged a conical construction, reminiscent of Chevreul (Chapter 15) and Lambert (Chapter 9). (He introduced this cone for the first time in 1893, in the second edition of his *Vorlesungen über die Menschen- und Thierseele* [Lectures on the Soul of Man and Animals]; it is absent in the first, 1863 edition, and it is not known why he decided to include it, since by 1874 he had already described his considerably more informative sphere.)

Wundt was mainly interested in color systems, with which he sought to learn more about the process of perception—those conditions of consciousness "which cannot be separated into more simple components," as he wrote in *Physiological Psychology,* a book which also included his color sphere. In it, white (WE) and black (SC) are placed at the poles, and the equator comprises eight colors—green (GR), green-blue (GB), blue (BL), violet (VI), purple (PU), red (RO), yellow (GE), and yellow-green (GG)—equally spaced around the circle, with gray at its center. Wundt also noted that, "Although this representation of a sphere is arbitrary, in that instead of it, another embodiment with similar properties can be selected, the psychological fact that the entire system of light sensations is a three-dimensional and self-contained continuum will still be vividly expressed within it."

In the case of the color sphere, one can move away from the largest cross-sectional surface (through its center) in two directions, while with the cone there is only one route, running from the white center of the circular base, up to the black tip. This circular base of the cone was allocated to only six colors—yellow, green, blue, purple, red, and

orange. The result of this restricted selection is that different colors are opposite each other (complementary) in Wundt's two systems.

The number eight plays a distinct role in both of Wundt's arrangements. A total of eight colors appear in the cone, with eight colors again appearing in the largest cross-section through the center of the sphere. In fact, if we take Maxwell's three primary colors as a basis (see Chapter 17), there will be eight basic colors representing the outer limits of the eye's perception of color; from three components, eight combinations can be produced, including both black (which does not contain a primary color) and white (which contains all three primary colors).

A special note is necessary at this point regarding the concept of the color circle appearing in both of Wundt's systems, which can of course be traced back to Newton. It seems extraordinary to have continued to portray colors by means of a closed circle after knowing that the visible electromagnetic spectrum (between 400 nm. [blue] and 700 nm. [red]) is open ended. But the color circle does not really exist except in our minds—the constructed achievement of our perception.

Colors show that our perception is actually both selective and constructive—selective because not all of light's wavelengths are received by the eye, and constructive because qualities (colors) arise from physical stimuli (light of varying wavelengths). By mixing two wavelengths, which remain separable physically, a third color is created, which from the physiological point of view is not separable; white and purple can arise here only by mixing (and not as pure colors).

We can still ask why our eyes are sensitive only to those wavelengths between 400 and 800 nm., and we can find the

answer in the atmosphere, which only permits the penetration of restricted wavelengths. The atmosphere of our planet is actually an "optical window," which essentially corresponds to our sensory perception. Our eyes are thus sensitive to just that section in which the electromagnetic spectrum of light reaching the earth is at its peak. This maximum is in the green area, in the middle of the spectral colors—the same area to which Bezold assigned the greatest space in his circle. Since this has arisen and been selected in the course of evolution, biologists speak here of the "adaptive character" of perception. The radiation reaching us is the only light we see.

EWALD HERING

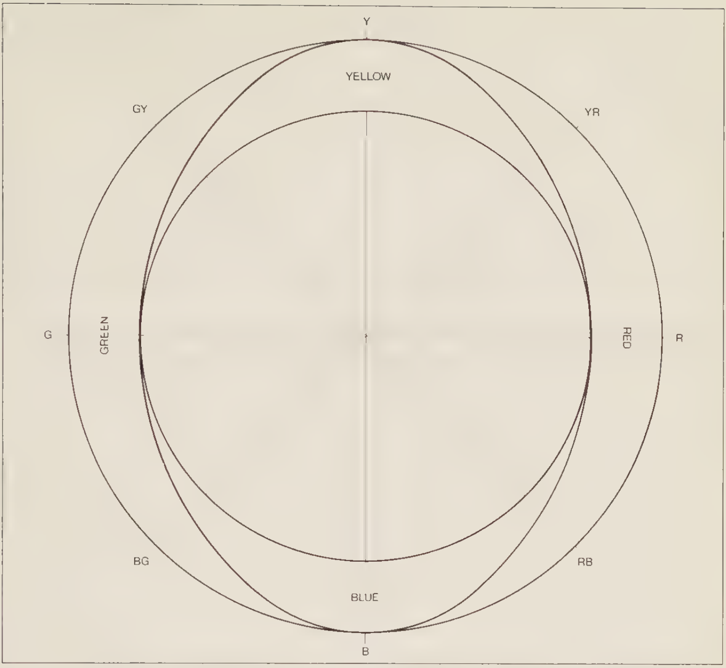
In the middle of the 19th century, it was accepted that only three variables, in other words three receptors, were required to explain the color mixing which formed the basis of experiments carried out by both James Maxwell (Chapter 17) in 1867, and Hermann von Helmholtz (Chapter 18) in 1859. Modern physiologists can confirm that only three types of photoreceptors exist, and that each type is particularly sensitive to either short, medium, or long waves. Although this observation can help us explain why some wavebands of incident light cannot be distinguished from others, and thus why many mixtures result in what appear to be the same colors, we are nevertheless unable to explain those color hues which we can see.

It was Helmholtz who had postulated that there must be three receptors, each directly signaling a definite color hue. Consequently, he named these receptors "blue," "green," and "red," in the belief that the blue receptor, for example, produced the sensation of blue, and so on. He was, of course, aware that the spectral sensitivity of the receptors had to overlap, so that each wavelength could give rise to varying color relationships (and other perceptions). Between 1872 and 1874, the physiologist Ewald Hering (1834–1918) had delivered "six communications" entitled *On the Theory of Sensibility to Light* at the Academy of Sciences in Vienna—privately published in 1878—in which he opposed Helmholtz's view of the phenomenon of

colors. (From 1905 onward, he published his *Principles of the Theory of Sensitivity to Light.* These appeared in four installments. The third, incidentally, was broken off in mid-sentence, leaving the reader to wait years for the rest!)

Although he also spent considerable time investigating the eye's perception of three-dimensional space, Hering was more concerned with the introspective aspects of colors. His work on color referred, for example, to the problem of yellow in the three-color system. According to Helmholtz, yellow was of necessity produced from a mixture of red and green, but this—as Hering realized—was not in line with human experience. The sensation of yellow is elementary, and not traceable to a mixture. Hering further stated that mixtures of red and green never occur, extinguishing each other instead. A red-green is simply inconceivable. He therefore concluded that there are not three, but four elementary color sensations or psychological primaries, which code our perception by means of so-called opposing processes. "Yellow can have a red or green tinge, but not a blue one; blue can have only either a red or a green tinge; and red only either a yellow or a blue one. The four colors," wrote Hering in 1878, "can with complete correctness therefore be described as simple or basic colors, as Leonardo da Vinci has already done. Language, too, has simple descriptions of them, and not expressions borrowed from colored natural bodies."

In the case of opposing colors, which account for all color hues of the visible spectrum, Hering also spoke of "antagonistic types of light . . . which together produce white." That meant "they do not complement each other to form white, but only allow white to occur as pure because, as antagonists, they render each other's effect impossible."



White was for him "a sensation of its own nature, in the same way as black, red, green, yellow, or blue." Hence, Hering additionally proposed a white-black opposing process, in order to account for brightness. There were thus six basic color hues in all.

Hering explicitly distanced his *Theory of the Sensitivity of Light* from the world of physics. To him, the claim that red and green or blue and yellow together give white would "only make sense if red and green are understood as oscillations of the ether, and not red and green sensations."

Experiments using test subjects to describe an impression of colored light now confirm Hering's opposition theory convincingly; four expressions—red, green, yellow, and blue—were available to the early pioneers, and they were able to describe each color using suitable combinations of

these terms. There are in fact four (and not three) fundamental color hues. (The neurophysiological proof has been available since 1966, and we shall look into this later.) And these are placed opposite each other in Hering's system, which is a circle of opposing rings and ellipses. This has been reproduced here with its four basic colors, yellow (Y), red (R), blue (B), and green (G), arranged at right angles to one another. The broken lines refer to mixtures at a ratio of 50:50: yellow-red (YR), red-blue (RB), blue-green (BG), and green-yellow (GY). On the lower right, we have stretched the circle out into a strip.

Hering's order of colors, which he described as "the natural system of color sensations," forms the basis of a system now known by the three letters NCS (Chapter 48), standing for the "Natural Color System." The succession of the color circle shows the position of the four "elementary" colors and the proportions with which any two elementary colors can form mixtures.

Hering's opposition theory was not accepted, being criticized chiefly by students of Helmholtz who argued that Hering's proposal only made sense if two different processes existed within the nervous system, namely stimulating and moderating processes. In Hering's day, the kind of knowledge which we now take for granted still had not yet been acquired or subjected to practical testing.

23

CHARLES BLANC

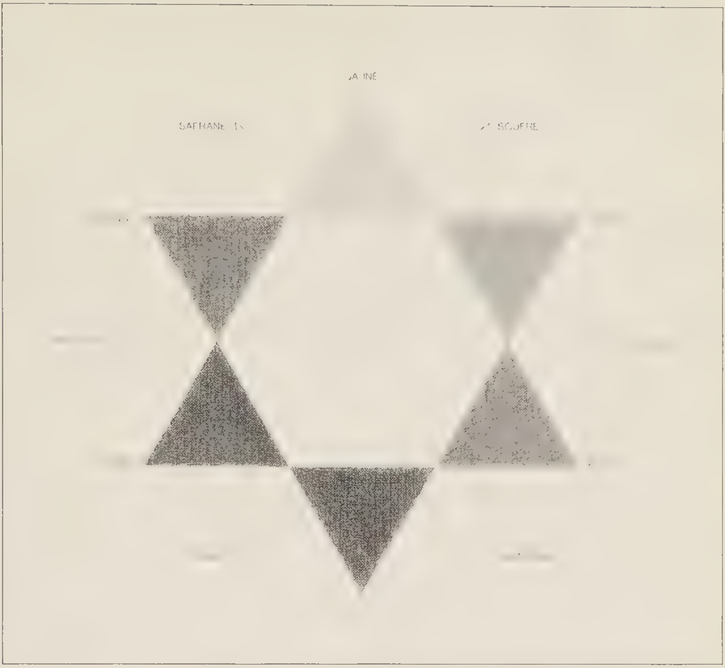
After the revolution of 1848, the French art critic Charles Blanc (1813–1882) was for some years the director of the Department of Decorative Arts at the Ministry of the Interior in Paris. He first pursued a political career there, but then developed his interest in art, and in 1881 presented his *Grammaire des arts décoratifs,* which was widely read by artists, including Gaugin, Seurat, and van Gogh. Blanc's writings are regarded as the most influential texts on color theory of the second half of the 19th century.

In 1879, two years before publishing his grammar, Blanc designed a color system based on Chevreul's "laws of simultaneous contrast" (see Chapter 15), also borrowing some ideas from the painter Eugène Delacroix, who had attempted to put Chevreul's theory of contrast into practice in his pictures. For Delacroix, half tones—the dominating principle of his painting—occur not as a result of pure colors being mixed with "dirty making" black, but by the use of neutralizing complementary colors. To systematize his ideas about colors, Blanc made an equilateral triangle with yellow, red, and blue on the corners; and violet (between red and blue), green (between blue and yellow), and orange (between yellow and red) on the sides. Blanc thus constructed his color circle from triangles without including black or white—three chromatic triangles, or one for each of the additive primary colors red *(rouge),* yellow *(jaune),* and blue *(bleu),* and one for each of their complementary partners orange, green *(vert),* and violet.

The mixed colors were described by reference to both materials and objects—garnet red, capuchin, saffron, sulphur, turquoise, and campanula. If orange is included, there will be four independent color terms which correspond to Hering's psychological primary colors (see Chapter 22).

Before bringing out his grammar of decorative arts, Blanc had written a grammar of painting and engraving (*Grammaire des arts du dessin*, 1867) in which he regarded colors as the "feminine" component of art, subordinate to the "masculine" of the drawn line. Although the artists among his readers apparently had little idea what to make of this distinction, they did support other of his ideas. Van Gogh, for example, was fascinated by the dynamics of complementary color pairs. Blanc had described complementary colors as victorious allies when they appeared side by side, but mixed together he saw them as deadly enemies. Van Gogh subsequently used them in his pictures to portray "struggle and antithesis," as he wrote in his letters to his brother Theo.

Blanc's main writings appeared around 1880, at a time when a new dialogue between the worlds of art and science was beginning. The heyday of Impressionism was drawing to a close, and in the following years the Neoimpressionists, under the leadership of Georges Seurat, would attempt to provide a more scientific basis for impressionistic colors. They had an abundance of material available to them—including the works of Hermann von Helmholtz (whose *Manual of Psychological Optics* had by then appeared in French) and Wilhelm von Bezold's texts, which were published in French in 1876. Seurat and his colleagues had begun to feel that if they did not become more involved in a science that could explain the optical effects which formed art's basis, it



would remain intellectually unsatisfying. Their task was made easier by the work of the physicist Nicholas Odgen Rood, who was also an accomplished painter. In the next chapter we will consider his order of colors, and show how he used them.

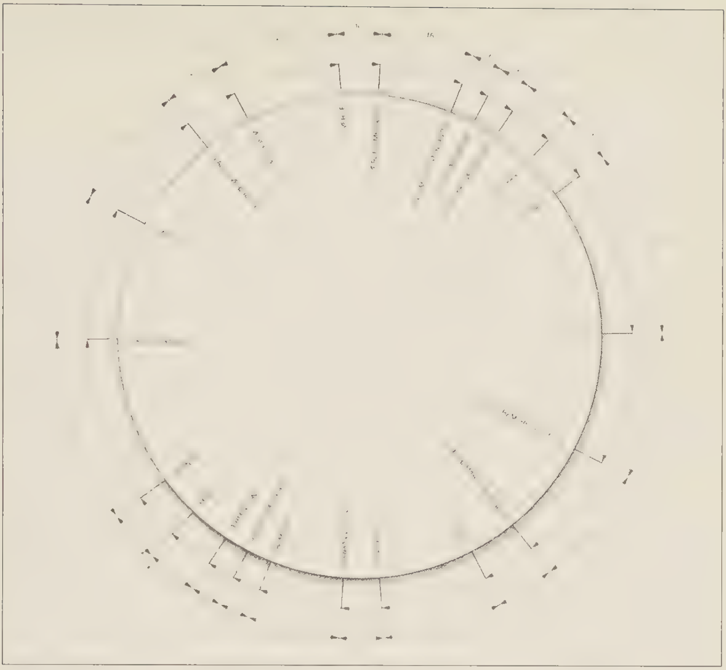
NICHOLAS ODGEN ROOD

The American Nicholas Odgen Rood (1831–1902) had studied physics before he started to paint during a visit to Germany. His interest in colors thus encompassed scientific and artistic points of view, and both aspects were behind his attempts to impose a systematic order on colors. His book *Modern Chromatics* appeared in 1879, promising "Applications for Art and Industry" in its subtitle. Rood proclaimed it as "an introduction to the facts, in a simple and comprehensive way, which form the basis of the artist's use of colors." A second edition of the work appeared two years later, this time with the less interesting title *Student's Textbook of Color.* In it he instructed artists on the insights of Helmholtz and encouraged them to "paint with light."

Rood's color system used concentric color circles for the first time, these being based on the primary colors red, green, and blue, and possessing a total of 12 outer segments of equal size (not shown here). The colors of these segments are red, orange, orange-yellow, yellow, green-yellow, green, green-blue, cyan, blue, ultramarine blue, violet, and purple. The circles become paler as they progress inward, with the center of the rings finally containing white.

(As a means of standardizing the colors, Rood also suggested a cylindrical color solid, with its circular cross-section accommodating 12 color hues, and changing from white to black along its height).

In addition to his rather conventional color circle, Rood produced the scientific version. The colors, with their



precise angular positions, are those actually used by painters on their palettes.

Rood's color wheel is a laborious improvement of Maxwell's triangle. As a physicist, Rood was interested in the additive mixture of colors, and he used the spinning color-tops devised by James Maxwell to help determine the exact position of individual colors and their predominance. His color mixtures were obtained by spinning color-tops carrying the primary colors at varying proportions (of surface area), with the resulting impression then being compared with an optical gray composed of black and white components. By varying the proportions of each primary color on the tops, it was possible to establish the relative proportions required to produce a colorless gray. The resultant proportions were then treated in the Newtonian sense,

as a mass attached to the end of a lever, with the length of the lever being adjusted so that the system remained in equilibrium. After a series of tedious measurements—not to mention some complicated formulae—Rood was able to produce a triangle (not shown here) which showed "the colors and the color hues according to their angular position, and their saturation or intensity through greater or lesser distancing from white," as stated in *Modern Chromatics.*

If Rood's circle is stretched into a column, a kind of psychological spectrum results. Compared to the physical (prismatic) spectrum (left-hand column), it shows the varying predominance of colors. (Here the horizontal lines signify the wavelengths of the specified colors.) Red, which so impresses our minds, and takes up so much space in the right-hand column, remains as a physical phenomenon prettily placed at the edge. What may be a priority for us is not necessarily so important in the physical world.

25 CHARLES LACOUTURE

In 1890, *Répertoire Chromatique* was published in Paris by the French botanist and naturalist Charles Lacouture (1832–1908). Lacouture was a professor at the Collège Clément in Metz and had already written many books on moss and other non-flowering plants when he presented his work on colors. In *Répertoire Chromatique,* he promised "reasonable and practical solutions" to the problems occurring with the multiple use (mixing) of colors, and constructed a figure which he called a "trilobe synoptique". As its name implies, it contains three lobes, and provides a comparative view of colors. Lacouture considered the three basic colors of red (R), blue (B), and yellow (J, *jaune*), using these colors in his original 1890 figure to plot the fine lines running in an arc, for example from the field J at the bottom left to the opposing field J at bottom right. Although not shown here, Lacouture reproduced the various color hues and tints not by altering the color of the ink he worked with, instead varying both the thickness and number of lines placed across his color fields, in each case progressing from white in six steps, R1 . . . R5, R. Each of the three primary colors appears as a generator of color fields, which all overlap.

The primary colors on the edges of the trilobe are effectively a register in which the central mixtures can be checked. The lines in this figure can be followed in the way

shown, allowing exploration of all the color fields until the start position is again reached.

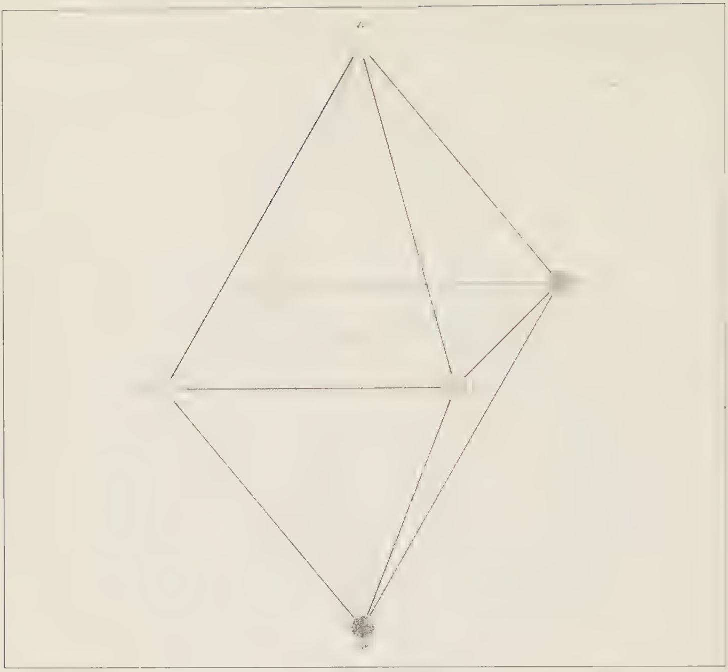
ALOIS HÖFLER

Alois Höfler (1853–1928), an Austrian educator and philosopher, produced many texts both on psychology and general science, and made a name for himself by publishing the Berlin Kant Edition (1903). In 1897, his textbook *Psychologie* appeared, in which he introduced his first color system—a double pyramid with a rectangular base (an octahedron). He later proposed a further, derivative color solid with a triangular base (a tetrahedron). White (W. above) and black (BK. below) are found at the tips of both constructions, with gray appearing in the middle.

Höfler also sought to relate the harmony of colors and music. In his books, he explicitly pointed to the sequence white-gray-black, since he discovered here a "quasi-straight line," meaning a straight line limited at both ends. Such a line, however, appears unfamiliar to music and musical notes.

The rectangle—the system of four—operates with the four elementary perceived colors: yellow (Y), red (R), blue (B), and green (G). Of these four psychological colors, only yellow (Y), along with cyan blue (C) and purple (P) reappears in the artist's triangle, which thus contains the subtractive primary colors.

The purpose of Höfler's arrangement was not to provide an organizational or identification system, nor did he consider that color variations can be subordinated, for instance to the geometric properties of a sphere. He was more concerned with "certain alternative internal relationships"



between the colors. His color octahedron not only represented Hering's basic colors, but also their relationship as opposing colors.

Höfler's solid can be seen as an expression of the relationship between color vision on the one hand, and the psychological effect of colors on the other. For this reason, many psychological textbooks have adopted his pyramids to provide information on our perception of colors.

Starting with the yellow common to both pyramids, we can construct a color circle possessing twelve individually spaced segments—the six named colors, together with the areas lying between them.

HERMANN EBBINGHAUS

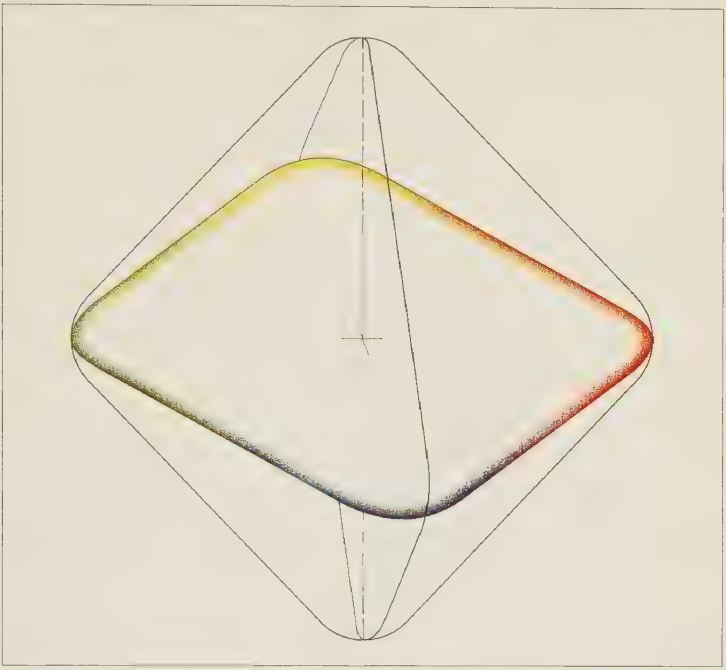
The concept of the double pyramid gained popularity at the turn of the century, and the German cognitive psychologist Hermann Ebbinghaus (1850–1909) also constructed a color system on this basis. He rounded off the extremities, however, and inclined the central plane. The color solid thus formed, containing the four primary colors red, yellow, green, and blue, linked an idea of Leonardo da Vinci to the realization that the chromatic colors vary in brightness and can thus be separately distinguished. In addition to the color solid itself, we have included (right) a few projections—more or less in the yellow-blue or red-green planes—to demonstrate the differentiation possible with this pyramid. The base-square of the double solid is tilted in such a way that the "best" yellow hues, which are relatively bright, are nearer to white, and the "best" blue tones, which are relatively dark, are nearer to black. Ebbinghaus rounded off the corners of his solid because the transition between the colors is not sharply defined. His system does not predict the mixtures of colors; it is a purely phenomenological—that which can be observed—portrayal, in which the complementary pairs are not even opposite one another.

Ebbinghaus published a Theory of Color Vision in the *Zeitschrift für Psychologie* (Journal of Psychology) in 1893, in which he pointed out, among other things, that the perception of colors can only be accomplished with the aid of "higher mental processes." As a psychologist, he knew of

the four elementary color sensations, and he also appreciated that the physiologists had a valid point when they maintained that in the eye's retina there were only three photosensitive substances with which to explain the phenomenon of color vision and its anomalies. In addition, Ebbinghaus had discovered that two white hues, which could be produced by spinning either red and green or blue and yellow colored tops, indeed appeared the same at certain levels of brightness, but appeared different when the illumination was reduced.

For a long time, the Ebbinghaus double pyramid represented the last stronghold of phenomenology, and it resisted the increasing dominance of physiology and its attitude toward the nervous system. Something independent of both light stimulus and physiological reaction could be demonstrated with the color pyramid. In the course of the following years, however, the phenomenologists were increasingly forced to clear the field for the experimentalists. With Ebbinghaus, an era in which colors were simple closed.

The moment was also to come when the world of physics could no longer be quite so certain about the nature of light. About 100 years after Young's experiments, in which interference between light waves seemed to prove that light possessed a wave character, an exact analysis of the interaction between radiation and matter revealed the probable existence of light particles. Albert Einstein was the first to point this out—which later gained him the Nobel Prize for Physics—but at the same time he also realized that one of the great cornerstones of physics had been removed. While Einstein spoke of the duality of light, the terminology of experiments made it increasingly evident that, to be graphically and comprehensively understood, light had to be



conceived in its properties both as a wave and as particles—the so-called photons.

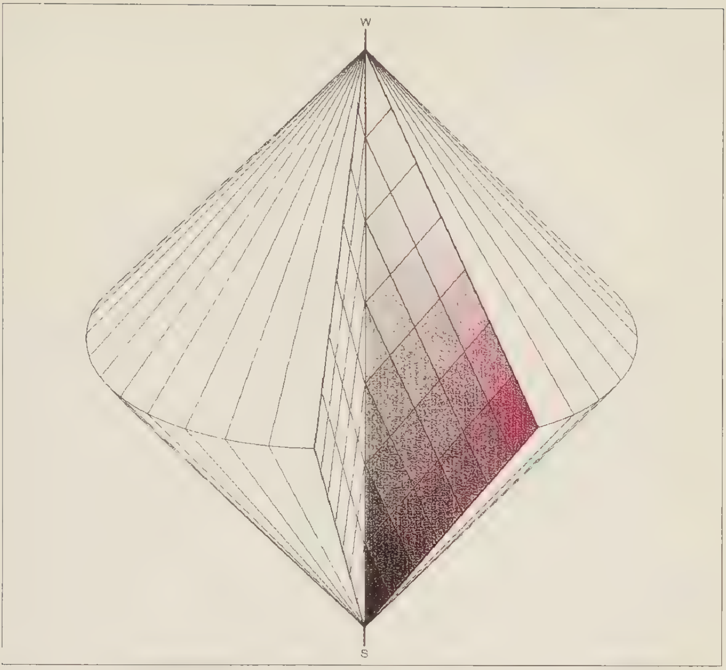
Colors are only formed after light has interacted with biological matter, and we are forced to the conclusion that these very same photons enable the retina to transmit a specific color to the brain. When it comes to color systems, however, we do not need to consult physics in such detail. Although the idea that waves are absorbed by the eye is sufficient for our purposes, what then unfolds within the brain is much more complicated.

38

ROBERT RIDGWAY

On his many voyages of discovery through the world of nature, the American ornithologist and botanist Robert Ridgway (1850–1929) had encountered an almost infinite number of colors. In the course of time, he also became aware that the accuracy required for a scientific description of colors would only be possible through some form of standardization, and he therefore proposed a color system which was published in 1912 under the title *Color Standards and Nomenclature.*

Ridgeway's system exploited the possibilities of additive color mixing. The basis for the required systematic order of colors was a circle, divided into 36 pure, solid colors (unalloyed with white or black) which perceptually were approximately evenly spaced. This circle appears here as the outer circumference of the figure, which also reproduces the numbering—from 1 to 71—as originally used by Ridgway. While each basic color loses saturation toward the center with the progressive, additive mixing of a medium gray, its hue remains virtually unchanged. Ridgway obtained his set of color standards as five steps—identified by concentric lines—between the outer ring of full colors and the central gray. To maintain their visual equidistance, the six concentric rings did not contain the same number of colors. To each of the 159 colors within the full-color circle, going along the up-down axis Ridgway added either white or black progressively, and eventually succeeded in achieving the three-dimensional diversity of non-self-illuminating

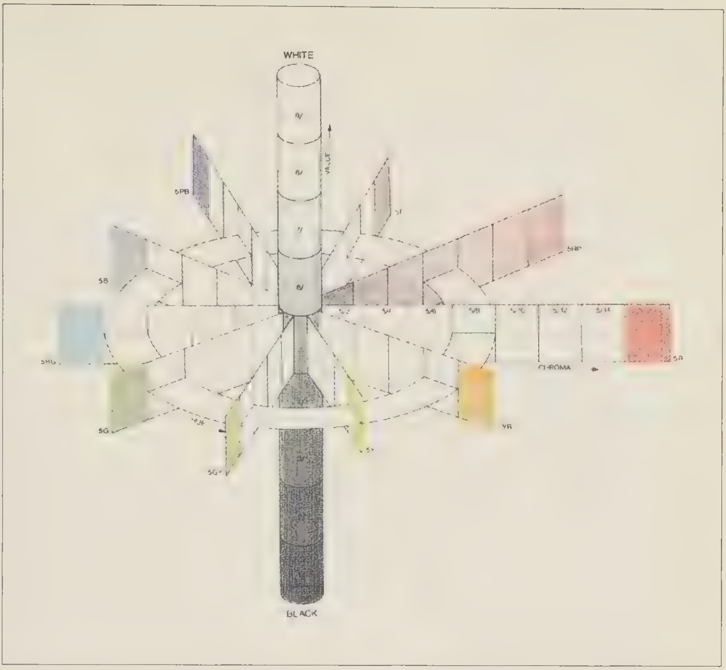


colors. Three steps are involved in each direction. Toward black these are called shades, and toward white they are tints. Ridgway thus created a register of 7x159=1113 colors, which with the two achromatic tips give 1115 color standards; with these standards, the colors of birds, insects, and flowers could be identified.

Alternatively, the three-dimensional arrangement of these standard colors could be illustrated by the (dissected) double cone. The full colors are placed around the equator, with the gray colors along the central axis from black to white.

29 ALBERT HENRY MUNSELL

The effort by the American painter Albert Henry Munsell (1858–1918) is generally considered the most successful of all the attempts to construct a color system that provides standard samples according to a logically organized plan, while also taking into account the perceived affinity of colors. His is certainly one of the most widely known and most commonly used color systems. It is based on the principle of "perceptually measured equidistance"—to use the correct, although rather long-winded technical term. When he proposed his rather inconspicuous color sphere (*A Color Notation,* 1905), Munsell was still influenced by N. O. Rood's *Modern Chromatics* (1879, see Chapter 24). But as he began to work with his painted samples, he realized that a geometrically symmetrical solid was unable to portray the opposing relationships between the colors as we perceive them. The variation between the brightness of pure chromatic colors is too great for them to be arranged in sequence along the equator; yellow, for example, is brighter than red, which is in turn brighter than violet. Munsell's efforts at constructing a system in which the spacing of each color to its neighbor could be perceived as equal culminated in the publication of his *Color Atlas* in 1915. He introduced an order of colors—also known as a "color tree" due to its irregular outer profile—grouped around a "naturally grown" central vertical gray scale.



Munsell constructed his system around a circle with ten segments, arranging its colors at equal distances and selecting them in such a way that opposing pairs would result in an achromatic mixture (compensativity). Munsell organized the hues of the hand-painted panels which make up the tree according to three variables, as included in his rather idiosyncratic system of naming. His parameters were hue, value (the index for brightness), and chroma (the gradations of saturation). Each color was characterized by a triple block, symbolically indicated as H/V/C—we will explain this below. With this as a basis, Munsell went on to develop his entire system using spinning color tops to define the mixtures, while entrusting the final judgment to his eyes.

The vertical value scale divided the area between black and white into ten steps (which Munsell determined using

a photometer of his own construction). He did not simply define these gradations according to linear changes in reflection, but selected a scale in which the square root of the measured reflected intensity was subjected to uniform change (see also Ostwald's system).

After setting up this value scale, Munsell selected samples from red (R), yellow (Y), green (G), blue (B), and purple (P) that, to his painter's eye, appeared to be equidistant not only from each other, but also from a gray of the same value. These five colors became the primary colors of his system. He also provided five additional mixtures—yellow-red (YR), green-yellow (GY), blue-green (BG), purple-blue (PB), and red-purple (RP). Making ten gradations between each of these ten colors, he obtained 100 steps of hue in arranging them in a circle around the previously mentioned neutral gray (N). The parameter chroma was arbitrarily assigned a level of 5 for these ten main colors and their mixtures. The chroma scale was open ended and could reach values of up to 12 and 14, depending on the intensity of the colors used. Vermilion, for example, reached the extreme, and was abbreviated as 5R 5/14 in Munsell's notation, while pink, which is less saturated, was defined as 5R 5/4; note that both have the same medium red hue 5R.

The outer graduations of the color circle show how a total of 40 hues are created by dividing the original five color-hue intervals between the main hues, first into 10, then 20, and finally into 40 segments, again in such a way that they will be perceived as equidistant.

A new *Color Atlas* appeared in 1929, after Munsell's death, this time entitled *Munsell Book of Color.* This is the edition we still use today. In 1942, the American Standards Organization recommended its use for specifying the colors

of surfaces. The approximate identification of Munsell's parameters, namely hue, value, and chroma, could be confirmed through direct visual comparison with the color panels themselves, but a refinement to Munsell's notation was recommended (to be later implemented in association with the Optical Society of America and designated as "renotation").

When specifying a material standard, it is most important to refer—using normal physical methods—to a basic model, to which all other color systems can be converted. Modern color researchers would have required that Munsell reconstruct his system using their modern color-measurement techniques. A unique arrangement might well have resulted, linking its highly sensitive perceptual assessment of colors to their non-empirical registration. The term "color valency" implies the property of a color stimulus which contributes to the effect of a mixture. Munsell, however, depended on mixtures derived from spinning color tops, which he then corrected so that any systematic deviations of perceived colors from the modern non-empirical approach were kept to a minimum. Munsell's colorful tree will blossom for many years to come.

30 WILHELM OSTWALD

In 1909, Wilhelm Ostwald (1853–1932)—who came from the Baltic coast of Germany—received the Nobel Prize for Chemistry for his work on catalysis, an area bordering on physics which promised applications in industry. Ostwald, instrumental in founding the first periodical in this area, *Zeitschrift für Physicalische Chemie,* was also something of a pioneer outside his own immediate field. He showed great interest in the history of his specialty, and in the physical sciences as a whole, as evidenced by his book *Klassiker der exakten Naturwissenschaften* (Classic Texts of the Exact Natural Sciences).

Ostwald explored many new approaches to scientific thought, although not always successfully; at one time he attempted to refute the existence of atoms as an unnecessary hypothesis, since their structure was invisible.

His final passion was the theory of colors, and after his retirement (at the age of only 53) he devoted himself to the laws of color, in the hope of developing a scientific basis for their perceived harmonies. His *Farbfibel* (The Color Primer), which appeared in 1916, introduced a color system devoted to this purpose (and continued on through fifteen editions).

Ostwald, who had met Albert H. Munsell (Chapter 29) in 1905 on a journey to America, attempted to devise a system—just as the American painter had done—based on perception and equalizing the respective differences between individual colors. Expressed in modern technical

language, we can say that Ostwald attempted to construct a perceptual color system using non-empirical methods. In place of Munsell's three parameters, Ostwald selected an alternative group of variables—namely color content, white content, and black content. He also introduced the special term "full color," by which he meant a color which permitted the sensation of a single color tone (Munsell's "hue") and was not tempered by white or black. To be more accurate, we could say that a full color was an optimally pure color, in other words of maximum saturation and at the same time bright. Full colors are, of course, ideal colors which cannot be reproduced by actual pigments. (When Ostwald published his color primer, his full colors contained about 5% white and slightly less black, as he himself conceded.)

We can thus formulate the guiding principle behind Ostwald's theory of color as follows: The most universal mixture is the mixture of full colors, plus white and black. Each pigmented color can be characterized by specifying its color content (at a particular color hue), white content, and black content. In his *Farbfibel,* Ostwald proceeded systematically, drawing a distinction between chromatic and achromatic colors. He arranged his achromatic colors in the form of a gray scale along a line containing eight gradations, which conformed to a geometric sequence. In other words, the influence of visually dominant white does not decrease uniformly going downward, instead it does so geometrically, with the perceived midpoint between black and white characterized by a proportion of approximately 20% white. (To avoid confusion, we have omitted the letters used here by Ostwald to identify these gradations.) The basis of the sequence is the so-called Weber-Fechner law of psychophysiology, although its application is technically limited. In fact, Ostwald later abandoned the gray sequence which used this law as its basis.

The full colors were arranged around a complete circle, borrowing from Hering's system (Chapter 22) and starting out with four basic colors, yellow to the north, red to the east, blue (more exactly, ultramarine) to the south, and sea green to the west. Four additional colors are then placed between these—orange between yellow and red, violet between red and ultramarine blue, turquoise between ultramarine blue and sea green, and leaf green between sea green and yellow. (Ostwald named orange "kress" and violet "veil." During World War I, it was considered prudent to avoid all words borrowed from the French. We will, however, not be so cautious.) As with Munsell, the colors

were so arranged that compensating colors (i.e., color pairs whose mixtures produced a neutral gray) were placed opposite to each other: yellow-ultramarine blue, orange-turquoise, red-sea green, and violet-leaf green. With these eight colors, Ostwald constructed 24 color hues with equal spacing, and numbered them starting with yellow, arranging them into a circle.

From the full colors of this circle, Ostwald then constructed the so-called "bright-clear" or "dark-clear" colors, two series going toward either white or black, which are "perceptually equidistant" from each adjacent color. With this construction, Ostwald could then proceed with the fulfillment of his original task, to specify the general mixing of the other colors. These he characterized as "dull colors" (or, in accordance with Hering, "veiled colors"), and they form most of the colors found in the color solid.

Each such dull color could be defined from a mixture of a full color and a gray tone, with the gray tone being defined from a mixture of black and white. The color standard desired for any particular full color could thus be realized using an equilateral triangle whose central black-white axis—the gray scale—lies opposite the full color in the third corner. The sides of the triangle running from the full color toward either black or white contain "dark-clear" or "bright-clear" sequences of colors. When joined onto the triangle of opposing complementary colors, such a monochromatic triangle—regarded as "psychological" by Ostwald—becomes a rhombus. This could be applied to the entire circle of pure colors, and in this way, the base of a double cone was created, uniting all the colors of Ostwald's system. *The Color Harmony Manual,* the third edition of which was published in 1948, provided a very

good practical embodiment of this construction. The word "harmony" in its title aptly symbolized what Ostwald wanted to achieve with colors. Experience had shown him (and others) that some color combinations were seen as pleasant (or harmonious), while others were unpleasant. The question was why, and whether a law explaining this could be formulated. With his analysis of color harmony, Ostwald proceeded on his conviction that harmony is created by color order. To identify these harmonies he even drafted a law ("harmony is order"), claiming he could find all harmonies by analyzing all the orders of color which his color solid—the double cone—allowed, and that he could do this according to the rules of geometry. From 1926 onward, these harmonies were summarized—initially by Ostwald himself—first in a *Harmothek,* and later in the *Color Harmony Manual,* with which we are already familiar.

It would not be fitting for us to overly criticize Ostwald's theory of color, but its effect does not appear very convincing. We probably have to accept that science does not provide us with information about the harmonious combination of colors in the same way as with sounds. Light and sound are different wave forms, and the eye, in contrast to the ear, possesses only rudimentary capabilities with regard to comparative analysis. In addition, we can barely see more than an octave (the maximal extent of the visible spectrum). There also appears to be no physical or physiological basis to the assumption that some individual combinations of color are more desirable than others. Nobody—including Ostwald—has ever thought of improving on the magnificence of a rainbow by removing or adding a component of its colors. However, Ostwald did wish to improve Japanese

woodcuts and recommended a new coloring, using his standards as a basis, henceforth to be regarded as more "Japanese" than the originals.

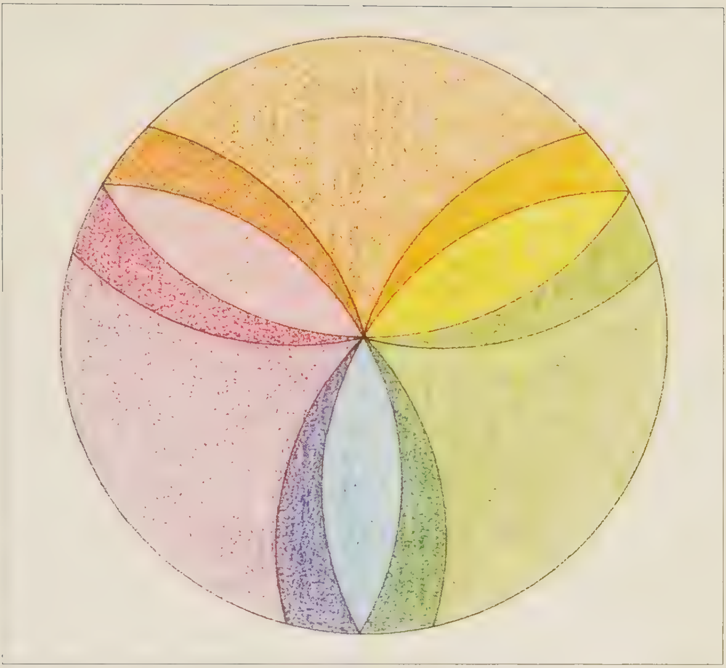
In the world of art, Ostwald may indeed have created rather a dubious reputation for himself with this claim, but his system nevertheless left its mark. For example, the Dutch movement *de Stijl,* with Piet Mondrian at its center, focused on his work—at any rate, Mondrian's treatment of colors in 1917 and 1918 had much in common with Ostwald's theories.

31 MICHEL JACOBS

In 1923, the Canadian-born sculptor and painter Michel Jacobs (1877–1958) wrote a book entitled *The Art of Color,* in which be presented some rather individualistic theories on the harmony of color. Jacobs had studied the decorative arts in Paris and New York, during which time he came to realize that, although art students learn first to draw and then how to apply color, to him the reverse seemed more sensible. To this end, he presented his theory of colors, but his aim was not to introduce a new viewpoint. Jacobs was a supporter of the ideas of Thomas Young and Hermann von Helmholtz. Thus he operated with three colors, although his selection—red, green, and violet—was rather peculiar. These he called "spectral primaries." The violet which he used is actually the type of blue-violet used by both Bezold and Helmholtz.

Michel Jacobs arranged his spectral primary colors around the circumference of a circle, placing them opposite three secondary colors which extended from the center toward the periphery. The latter were yellow, blue, and crimson, which Jacobs named "pigmentary primaries" and which, together with his spectral primaries, formed three pairs of complementary colors—the so-called "complementaries." The circle was laid out in such a way that this opposition also involved the opposition of concave and convex.

Using these reference colors, six mixtures are possible, which Jacobs named within structures unfolding like the



calyx of a flower. Going clockwise, these are orange, yellow-green, blue-green, blue-violet, purple, and scarlet. The complementary pairs may indeed flow into one another—purple and yellow-green, for example—but their separation is also emphasized. Generally, the many lines of the three calyx shapes actually maintain the separation of sharp extremes of complementary colors and reduce their contrast.

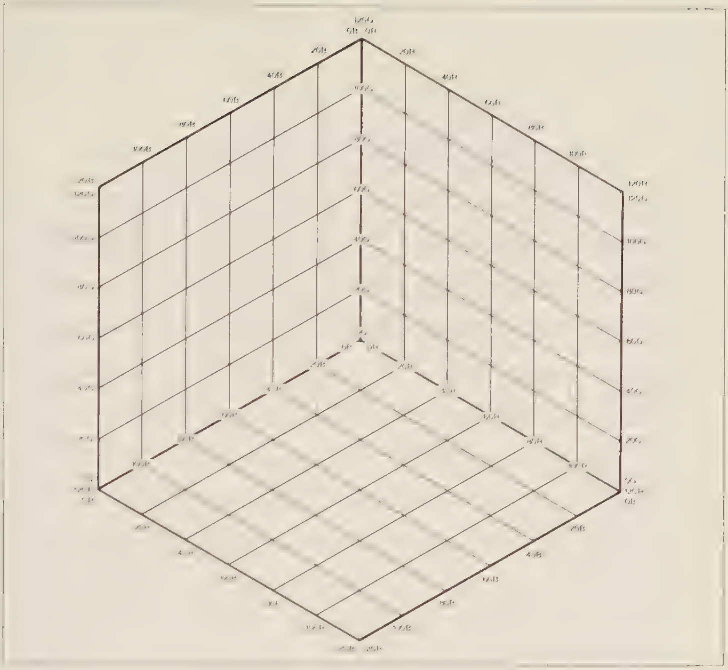
In his book, Jacobs stressed the psychological significance of color combinations, and we have shown some possible variations in the small circles. We could almost envisage them as faces, trying on a collection of masks.

32 MAX BECKE

There is only one correct color system, and that is the three-dimensional system of nature, with its three separate and independent effects of the three natural and original colors of pure yellow, pure blue, and pure purple as organizing and guiding principles, which orders all colors"—this was Max Becke's creed.

Becke was director of the textile industry's research institute in Vienna, and in 1924 presented a *Natural Theory of Colors*, in which he demonstrated with total conviction "that the scientific basis for the theory of colors is without question laid down in an irrefutable law of nature." Becke established that "the innermost essence of colors" shows through "as the objective properties of matter," and that "inevitably, through the process of sight in combination with this property, color terms identical to the colors" will be formed. The justification of his "natural color equation $x \cdot^{y} \cdot z$" is thus inferred, "because only this equation can accurately and scientifically express the actual relationships between cause and effect in the natural order of events."

Becke's stirring enthusiasm for the omnipotence of nature has long been relegated to the past, and in spite of all its proclaimed clarity and exactness, his "natural" theory of colors remains just one of many. As stated, it operated with three basic colors, which the Viennese chemist and dyer also precisely named, referring to specific pigments. Pure yellow should appear "as chinolin yellow on wool,"



pure blue "somewhat less pierced with green, as patent blue on wool," and purple should be "something like sulfurhodamine B extra on wool."

The objective of Becke's system was "to examine the laws of material coloration and the effect of colors," in other words, to cope with the subtractive mixtures of colored materials just as effectively as physicists dealt with the additive mixtures of colored light. To this end, he constructed a "natural trichromatic solid" (shown above in planar form) in which "the totality of the material colors in the world around us, and the conceptual color terms which are identical to them, is characterized and organized by means of their constructive content, according to the three original or basic colors." Becke then went on to describe both the construction and his idea more exactly. With our modern

attitudes, however, we may be surprised at the naïve simplicity with which the chemist saw the notional world within us:

"The natural color solid—shown as a cube—can be separated into three systems of vertical square surfaces of pure yellow, pure blue, and pure purple, which are graded from 0 to 120. Each material color in the outer world is, as a notional color term, mathematically and geometrically arranged at the intersection of the three basic color surfaces to which they have been allocated as a result of the inevitable disintegration of their objective general effect into these three independent and objective partial effects during the process of sight. The allocation of each color attains clear expression through the color equation $x^{y}z$, as entered into the triangular shape." Using this method of notation, white becomes $0^{0}0$, and black $120^{120}120$, with the three pure colors expressed as two zeroes and a 120. Becke referred to these as "one-third colors," and middle gray was characterized as three times 60.

His trichomatic solid contained four so-called counterpole axes, running from white to black, from pure yellow to full violet, from pure blue to scarlet, and from pure purple to full green. The complementary pairs are thus also included. If we rearrange the chromatic colors—which are dominant in Becke's cube—adjacently at angles of 120° and describe them as energy sources whose effect is revealed by means of concentric circles, we obtain a figure, which is better able to bring out the tension existing between the colors than the strictly cube-shaped construction. But the best illustration of this approach to color is Becke's own view, "Color is energy bound up in material."

33 ARTHUR POPE

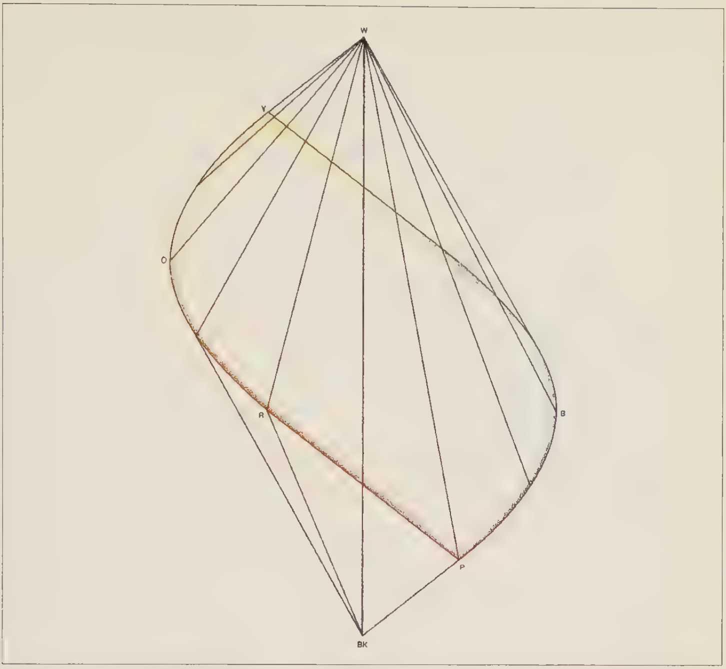
Although American art theorist and educator Arthur Pope (1880–1974) constructed his color solid in 1924, another twenty-five years were to pass before it was finally published. His system was centered on a gray axis, divided into nine gradations, running between white (W) and black (B). The solid itself can be envisaged as a series of triangles which vary in both size and shape. The two-dimensional projection of the three-dimensional arrangement results in a circle divided into twelve segments, one for each of the main colors: yellow (Y), green-yellow (GY), green (G), green-blue (GB), blue (B), blue-purple (BP), purple (P), red (R), orange-red (OR), orange (O), and yellow-orange (YO). Hue, saturation (called "purity"), and brightness were chosen by Pope as the main features of color perception. Tryggve Johansson's color system (Chapter 41) had a similar layout to show the color qualities which apply for any given color hue. Sven Hesselgren (Chapter 44) attempted a synthesis in other, similar experiments, based on Hering's psychological approach (Chapter 22), paving the way for the NCS system (Chapter 48). From a geometric point of view, Pope's system falls somewhere between Ostwald's graphic double cone and the calculated solid of Luther and Nyberg.

This is an appropriate point to review the experimental evidence for Hering's four-color theory, just as we did with the Young-Helmholtz trichromatic theory (see Chapter 14). We have already mentioned that molecular and biological

proof was provided in the 1960s for the theory that the eye has three receptors corresponding to three basic colors. The first step toward the perception of color on the retina is actually just as Young and Helmholtz envisaged. The second step, however, is more sophisticated. What the light-sensitive retinal cones actually register is not transmitted to the brain directly, as if each retinal cone served one nerve cell, which in turn continued to the brain. Rather, numerous retinal cells are interconnected before their combined information is passed to a nerve fiber. Discoveries made in the 1960s and 1970s showed that the processing of this visual information is organized in such a way that one nerve cell (a ganglion cell) transmits a signal when a specific area in the eye is excited by a specific stimulus. This area, which we can imagine as a tiny circle, is called the receptive field of the ganglion cell. The stimulus takes place either when light is present at its center but not at its edge, or, for other cells, the reverse. Here, physiologists speak of "on-center" and "off-center" cells. An "on-center" nerve cell will trigger its strongest signal when its receptive field is centrally illuminated and it its periphery remains dark. An "off-center" cell, in contrast, becomes active when the periphery of its receptive field receives light, and the center none.

Up to this point, we have not mentioned color. But on the strength of this fundamental insight into the processing of visual information, we could well ask if corresponding receptive fields for color exist, and the answer is yes. They take the form of a mechanism originally postulated by Hering in 1878, when he discussed the opponent cells of color perception.

As demonstrated by neurophysiologists in the 1960s and 70s, there are also "red-green" ganglion cells in the brain



which will become excited when red appears at the center of their associated receptive field, and green at the edge. Red at the periphery will inhibit such a nerve cell, as will green at the center. Green at the periphery, on the other hand, will stimulate a nerve signal.

Similarly, "blue-yellow" ganglion cells have also been detected, so that in the context of the "on-" and "off-center" cells mentioned above, we have established the existence of a physiological equivalent to the three opposing processes predicted by Hering—red-green, blue-yellow and black-white. (To be totally accurate, red, green, and blue are sensed directly by their retinal cones, while yellow is created by a mixed signal from the reception of long and medium wavelength light. The fact remains, however, that our impression of yellow seems unmixed.)

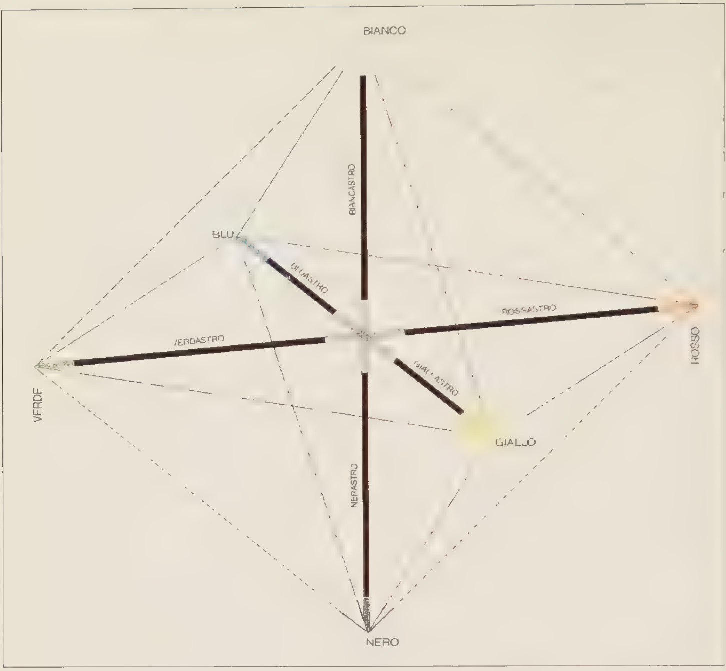
Although with these opponent cells we have found a second step in the visual processing of color, nobody can really say how many further steps on the way to consciousness are still to be discovered and understood. At the present time, we can only say that somewhere "further on" the opponent cells connect with neurons in the cerebral cortex and function as a sort of double opponent cell. In other words, a few will become active, for example if the receptive field at their center receives red, but not yellow, with yellow at the periphery, and not red.

Further investigation into the higher levels of color processing will no doubt follow these initial physiological inquiries. Color vision involves many phenomena which remain unexplained on a molecular and cellular level—simultaneous contrast (as described) being one example. The greatest step still to be made is an explanation of how the brain manages to maintain a constant impression of a color—for example of a leaf—in ever-changing conditions of ambient light; or why white paper always appears so, whether in the light of the midday sun, at sunset, or by the light of a table lamp. Of course, from an evolutionary viewpoint, colors can only make sense with such constancy and stability, and to this day they continue to be as wonderful as they are mysterious.

34 EDWIN G. BORING

The American psychologist Edwin G. Boring was a great admirer of Hermann von Helmholtz, to whom he dedicated his definitive textbook *Sensation and Perception in the History of Experimental Psychology* in 1942. In the specific area of color, however, Boring was more inclined toward the theories of Hering, who, as one of the leading cognitive psychologists of his time, had used his color system from circa 1878 to argue that Leonardo da Vinci's ideas—involving six primary colors, two achromatic, and four chromatic—were correct. Hering never carried out experiments as proof, preferring to investigate his own color perceptions through the process of introspection. Today we call this "phenomenological analysis," the word "phenomenon" (literally, "appearing") therefore implying that a distinction must be drawn between an appearance and the event that that appearance proclaims. Hering's color system is therefore based on such an analysis.

A few 20th-century psychologists have followed Hering's example, and Edwin G. Boring is among them. In 1929, Boring proposed a double pyramid, the central plane of which fills a rectangle, and the corners of which are occupied by Hering's four chromatic complementary colors: red *(rosso)* and green *(verde)*, or yellow *(giallo)* and blue *(blu)*. The achromatic colors white *(bianco)* and black *(nero)* are placed at the tips of the pyramids, with axes of increasing chromaticity extending outward from the gray center.



These are whiteness *(biancastro),* blackness *(nerastro),* redness *(rosasstro),* yellowness *(giallastro),* greenness *(verdastro),* and blueness *(bluastro).* In the 1950s, the psychologist F. L. Dimmick returned to Boring's system, in order to investigate the capacity of individuals to differentiate between colors; a high level of sensitivity is required. He pointed out that in this connection, the gray of the center tends to separate more than it combines. As a result, Dimmick does not have an uninterrupted series running from black through to white, for example, or from red through to green—instead, he introduces two consecutive series, one running from black to gray and the other from gray to white, or from a primary color to gray, or from gray to its complementary color. Dimmick also uses the linguistic argument in support of his separation—ultimately,

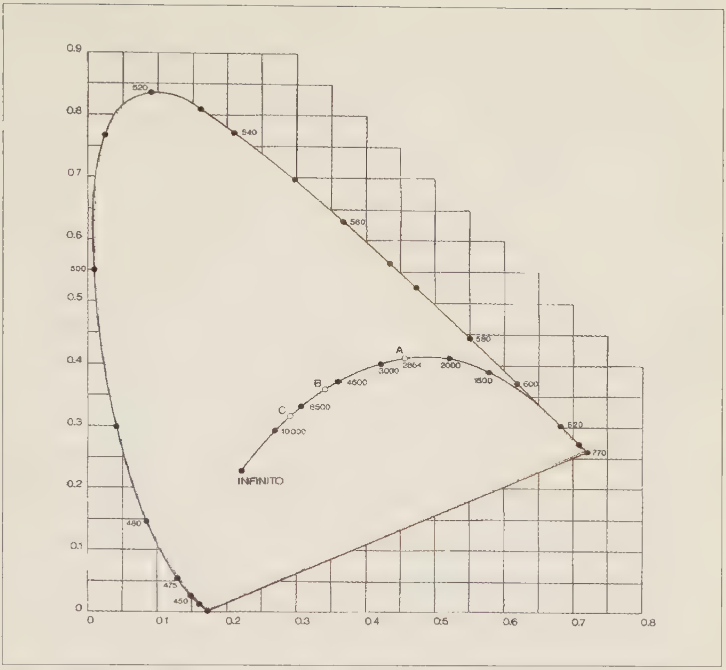
nobody refers to a blackish white, although we can talk of blackish gray; and nobody knows of a greenish red, although we can all imagine greenish gray.

CIE—1931 SYSTEM

Mathematical constructions certainly can have an aesthetic appeal, and the color diagram shown on the following page is a good example. This type of diagram, known as a "Standard Color Table" or "Standard Valency System," meets the requirements of professionals for precision and objectivity. We are already familiar with some systems (Chapters 29 and 30) which are able to specify colors exactly. For this purpose, a set of color samples was needed. But if such systems are to be used for color measurement (colorimetry), some problems will arise. The quantification of either a sample or a light source against a standard remains a very subjective procedure and, in addition, the samples used in such a comparison can fade with time, making them unreliable.

In the early 20th century, the need for an objective method of determining colors became increasingly apparent. A color system was needed that did not require the use of samples, and the CIE (Commission International d'Eclairage) was accordingly engaged to produce a corresponding "Color Standard Table." The result has been available since 1931, and without any doubt has withstood the test of time. The CIE chromatic diagram, which can be compared with the shape of a sugar loaf, horseshoe, or tongue, has a pedigree going all the way back to Maxwell's color measurements and the construction of his triangle (Chapter 17).

The starting point was the indirect method of comparison which we have already described ("color match"). Here,



a color is measured by permitting an observer to compare it, using a suitable apparatus, with (additive) mixtures of three elementary colors. The term used here is the "tristimulus value." "Color" in this case means "wavelength," and using the method described, we can establish the proportions of red, green, and blue which will be seen in light with a particular wavelength, for example of 520 nm. An observer makes the appropriate adjustment of these proportions with his apparatus and the result obtained is recorded as three numbers, noted with the letters R, G, and B. (We are dealing here with the measurement of the energy of the specific radiation, but this is of no consequence to the CIE diagram.)

Such experiments have been providing the basis for objective color measurement since the establishment of "color

matching functions" in the 1920s, mainly by W. D. Wright and J. Gould in England. Wright and Gould asked a large number of people with normal vision to manipulate three constant energy sources of monochromatic light (light of only one wavelength), in order to achieve a match with the primary colors. From the tristimulus values thus obtained, mean values could be derived which in turn were used to construct the color matching functions by plotting their position according to wavelength. These figures were accepted by the CIE in 1931, and related to a hypothetical "standard observer." At the same time, the CIE stipulated that a color sample was to be measured under conditions of average daylight, identified as 'C', which at that time still had to compete with a defined artificial light source 'A' and the sunlight of midday 'B' for recognition as the standard reference. (These letters can be seen in the diagram.)

The CIE adopted these measured color matching functions, but not without first giving them a mathematical twist, so that only positive values would arise for the new color matches. This certainly proved advantageous for making calculations, but caused a loss of clarity in the reference values used. While the old Maxwellian trichromatic values R, G, and B could still be related to primary colors, this was no longer possible with the CIE's new "tristimulus values" of X, Y, and Z (even though these were chosen so that white was represented by equal values of X, Y, and Z). But they can still be converted or normalized in the same way as Maxwell had done, and the result is the color table shown.

The CIE wanted to promote the study of colors using a color map, similar to the way the study of geography is simplified by using two-dimensional maps. In order to omit

one dimension, three new variables, x, y, and z (color masses) were derived from the three measured values of X, Y, and Z by dividing each of these numbers by their total sum: $x=X/(X+Y+Z)$, and so forth. The point of this conversion is that the sums of the color masses now always add up to one ($x+y+z=1$). Thus only two of the new values are independent, and these can be shown on a two-dimensional chart (indeed a map). This is the CIE diagram. The horizontal axis represents the values for x, and the vertical axis the values for y.

The chromaticity diagram shown will result if a line is drawn through the points which plot the positions of the converted tristimulus values for the various specified wavelengths. Since the range of wavelengths between 770 nm. and 450 nm. involves the spectral colors, we also call these positions *spectrum loci.* If spectral light with a wavelength of 400 nm. (left-hand edge intersection) is mixed with light of 770 nm. (right-hand end point), we can see that all resulting colors must lie on the straight line connecting these two points, the so-called purple line, which completes the diagram.

Although the CIE diagram is based on the ability of the human eye to match colors, it is a mathematical construction all the same, with the advantage that the position of each color can be calculated in relation to each of the primary colors, independent of any particular source of illumination. The chromaticity diagram has the added significance that all existing colors must lie within the tongue shape delineated by the two lines just mentioned. The light sources A, B, and C must first be specified, however. They are located on the curve marked with numbers, which represent temperatures, based on a law of physics which states

that light radiating from a black body—hence a color—is related to its temperature. For example, as glowing coal or boiling steel are increasingly heated, the color will change. Colors and temperature are interrelated; physics states that the midday light of the sun has a value of 4870° Kelvin, and a typical incandescent lamp about 2854° K. The light of the rising sun is approximately 1800° K. (Kelvin is the unit of value on the absolute temperature scale; 0° Kelvin [absolute zero] = -273.16° C.)

The CIE diagram is only one plane within a color space which records the sensation of light. Other planes represent colors of lesser brightness); in other words, the various diagrams show how colors will appear when there is less light. This projection of the *spectrum loci* and purple lines to the zero point result in a pretty construction, called a "color bag" in the sober world of colorimetry.

Besides the measurement of color, the CIE diagram can also be used to name colors. The division was originated by Kenneth L. Kelly, who proposed a name for each zone. The largest zone accommodates green, while red occupies only a small area opposite. This non-uniform division of space is, incidentally, often seen as a disadvantage of the CIE diagram. The oval surface around the center remains devoid of any particular allocation of names, and the standard light sources such as 'C' lie inside the dotted line. The CIE diagram can also assume many other functions. As a kind of color circle, it permits the fixing of complementary colors which, in additive mixtures, produce either white or gray. It also allows the prediction of the colors obtained by mixing light. It has served colorimetry well during the past six decades.

36

R. LUTHER N. D. NYBERG

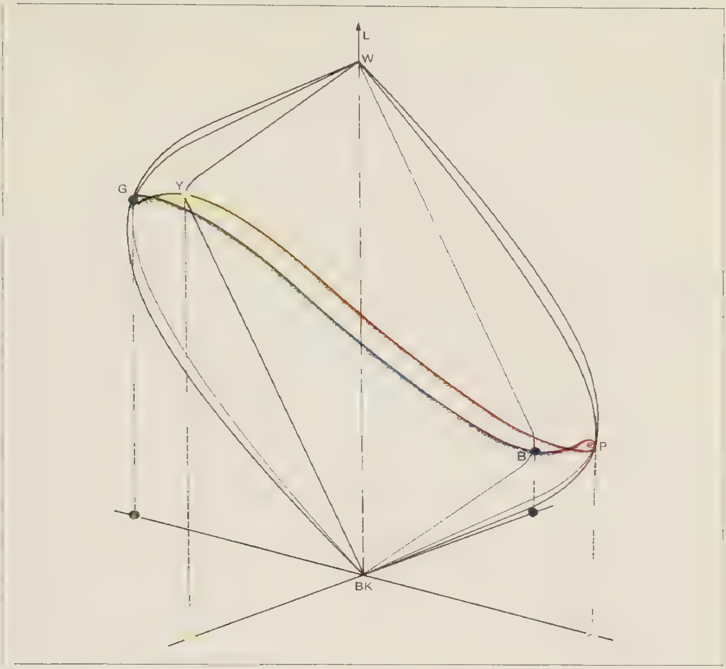
In 1927 and 1928, the physicists R. Luther and N. D. Nyberg each published a scientific work in which they described new developments "from the area of colorimetry and chromatic stimulus," and commented on "the construction of a color solid within the context of all light sensations." Their interest was centered on the figure or "solid" which would be revealed through accommodation of the tangible, material color pigments within a theoretical construction called a color space, and they were eventually able to provide a new spatial order for the diversity which colors exhibit.

To the outsider, the method used in the compilation of the system and its supporting structure is as baffling and confusing as the figure is beautiful. We encounter the mathematical world of colorimetry for the first time—a world where colors are characterized by numbers and their mutual relationships are made measurable. To be more specific, we see the measurement of color stimulus. Color stimulus is defined as the radiation that enters the eye and is absorbed there. Using three parameters, colorimetry experts can account for many possibilities, specifying the three dimensions—similar to the geometrical factors of height, length, and width defining the material space in which we move—used to define the boundaries of a so-called color space. The dimensions employed by Luther

and Nyberg involve two so-called "color moments" to define the plane which rises in the figure's color solid, together with the so-called relative brightness value L, which is perpendicular to this plane. The relative brightness value shows the brightness of a non-self-luminous color as the eye will value it. This is always compared to the brightness of other bodies viewed simultaneously. Color moments characterize the different types of pigment and colored materials in a technically verifiable way.

Luther and Nyberg returned to Ostwald's color circle, which was constructed with eight full colors (designated by Ostwald as yellow, orange, red, violet, ultramarine, turquoise, sea green, and leaf green), from which 24 color hues ultimately arise. In Luther and Nyberg's color solid, the full colors assume the position indicated by the curved line Y-G-B-P: yellow-green-blue-purple. In addition, the concept of optimal color is exploited. Optimal color is defined as being the brightest possible non-self-luminous color of a specified colored pigment or material.

We can imagine the figure as a reconstruction of Ostwald's double cone, but the only component still recognizable is the connecting line between the white and black points (W, BK), on which all the gray tones lie. The surface of this pigment color solid is formed by the full range of optimal colors. With a given color hue and a given brightness, the optimal color possesses the maximal saturation. And conversely, with a given hue and a given saturation, the optimal color will have the greatest brightness. Since color hue and saturation together determine the stimulus type, and since vectors for the same stimulus type within the color space are parallel, the optimal color vector can be distinguished from vectors of the same stimulus type by its



maximum possible length, so that it will always reach the surface of the color solid.

The exact, if rather asymmetrical, design of Luther and Nyberg's color solid has been constructed according to a relatively complicated series of formulae, in accordance with the criteria of stimulus colorimetry. Results can be plotted according to units of brightness or stimulus. One figure is based on units of stimulus, while brightness is given priority in the other figure. Here, a slightly more abstract portrayal has been selected, with the Luther-Nyberg solid suspended above a triangle defined by the lines between X, Y, and Z, inside of which the CIE curve has been drawn (compare with Chapter 35). The critical coordinates are the straight lines—the color moments—which bisect two corners of the triangle (at X and W) and intersect at right

angles. The lines drawn through the solid—named height layers—depict the positions where the optimal colors have the same relative brightness values.

There is no need to master all the technical details in order to enjoy the shape of this color solid. But it offers the expert an additional advantage, in that the optimal colors, accentuated within this color solid, permit a convenient theoretical approach to the problems of color photography, as well as four-color printing. In fact, although the accuracy offered requires a high degree of mathematical or geometric complexity, the effort involved is rewarded, since the Luther-Nyberg color solid is the colorimetrically equivalent shape of many other empirically conceived color solids—in conformance with the subjectivity of the eye.

It is amusing to think that just when these two physicists were striving to replace the subjective element in the construction of color solids with objective criteria, their colleagues were being compelled to a radical change in the way they viewed atoms. In the mid-twenties, it was becoming ever more obvious that the influence of the observer, even in the exactness of physics, could no longer be ignored, and that a subjective component was unavoidable. The dualism discovered by Einstein with regard to light (see Chapter 27) demands an understanding of light as both a wave formation and particles, to the extent that the observer—the subject—must choose for himself between these two aspects, and how he wishes to view the object of his investigation. But objectivity can still remain on a higher level, as philosopher-physicists were quick to realize, and since then the specter of subjectivity has lost some its horror. In the traditional sense, science can never be entirely objective—ultimately it is a human construction.

37 CIE—S. RÖSCH

Optimal colors are theoretical constructions defined by physical concepts. A transparent body can be said to possess an optimal color if, at a predetermined wavelength, it either permits all light to pass through it (transmission), or blocks all light. An opaque body of optimal color either reflects all light of a particular wavelength (remission) or absorbs it completely. Of course, no pigments or dyes exist which attain these properties perfectly. Nonetheless, optimal colors belong to the diversity of all conceivable non-self-luminous colors, and our plate is concerned with these colors (and not with self-illuminated objects). As can be seen, all realizable non-self-luminous colors lie within the color solid first described in 1928 by the German mineralogist S. Rösch. The surface is taken up by the optimal colors. As implied by the title of his work, Rösch wanted to facilitate the "Classification of Colors."

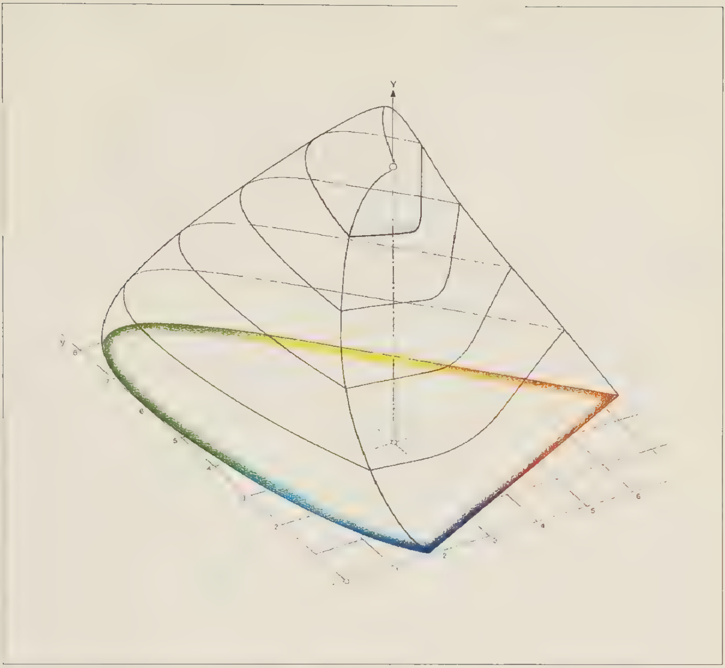
For additive color mixing and its measurement, the term "color valency" is often used by experts, rather than "color" alone. A color valency is specified by the three numbers (Chapter 35) which form the basis of the CIE system. These numbers specify the value of a color stimulus for an additive color mixture. We can thus state, rationally and correctly, that with color valencies pertaining to the same color pigment or colored material, the optimal colors are the brightest; conversely, with color valencies of the same brightness, the optimal colors are the most saturated. The

degree of brightness of a color is given the so-called relative brightness value, in comparison to a pure white.

Special diagrams permit the brightness of the optimal color to be ascertained for any given pigment or material. If this parameter is integrated as a third dimension into the CIE diagram P, the Rösch color mountain will be created, rising above the point C, the symbol for the standard light source. The planes, which become smaller and brighter toward the tip, each contain colors of equal brightness, and in the diagram represent the values 0 (the original CIE diagram from Chapter 35), 20, 40, 60, and 80. With 100, the mountain reaches ideal white, and thus its summit.

If we use the CIE diagram for colors created by scattered, refracted, or reflected light, not all regions within the tongue-shaped surface (as defined by the spectral curve and the purple line) can be occupied. Instead, there will be a restricted area for these non-self-luminous colors, also dependent on luminance. This factor accounts for the selective change which a body imparts on light rays. And using this factor as a reference, the area available within the CIE diagram can also be calculated.

Following Rösch's lead, the American psychophysicist D. L. MacAdam became the first to define this area exactly, and for this reason experts now refer to "MacAdam limits." We show these limits as they occur at a luminance factor of 0.3. The positions of 22 non-self-luminous colors have been plotted in this diagram, which can partly be derived from standard tables based on Munsell's system. The three green hues which appear in the upper area possess (from left to right) the values 5G 6/10, 10GY 6/12, and 5GY 6/10 according to Munsell's notation (hue, value, and chroma). In our everyday language, we would perhaps refer to these



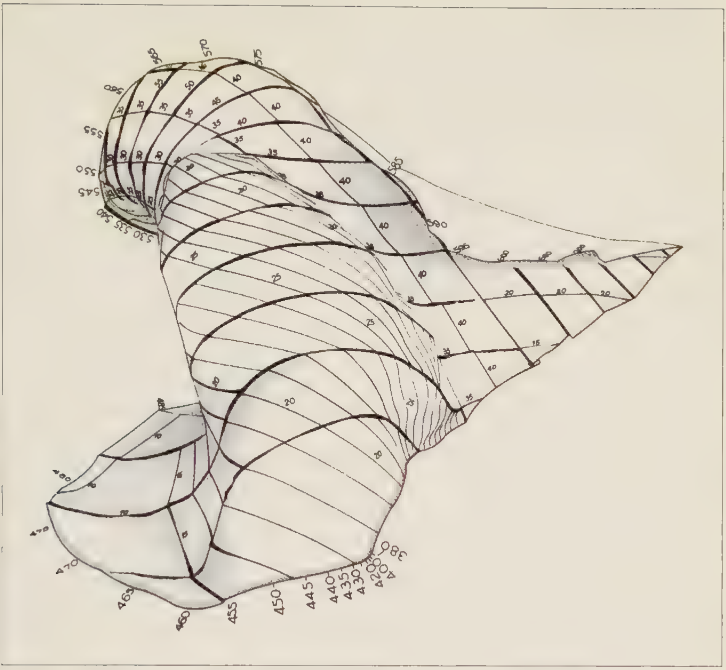
as brilliant green, light yellow-green, and deep yellow-green. In Munsell's notation, no further full-integer values can be given to the three color hues assigned to the lower right, at the end opposite green. But we can still give them names—we could call them, from left to right, dark pink, deep red-orange, and brilliant orange.

38 CIE—DOUGLAS L. MACADAM

The basis of this and the following chapter is the CIE standard color scale (Chapter 35). It has been altered, distorted, or transformed in such a way that a "Uniform Chromaticity Scale" (UCS) has been created—a type of "Uniform Color Scale." Ideally, colors should be distributed within it so that the spacing between them is as proportional as possible to their visually perceived differences. UCS diagrams are not actually color systems, because they are not represented by color standards and only cover a small area of color space. For the practical measurement of color, however, they are important.

We cannot examine here the many mathematical details worked out in 1944 by Douglas L. MacAdam, the former chairman of the Optical Society of America, for his paper "Concerning the Geometry of Color Space." These calculations were made just to arrive at the diagram shown here, which attempts to show small differences in color graphically. For our purposes, it is more important simply to enjoy the variety of geometric forms, which in turn bring forth the diversity of colors.

The starting point on the way to the illustrations shown here is the tongue-like CIE diagram. MacAdam first broke it down into uniform-sized squares. These squares were then transformed into strips which are so arranged that the original sequence of the former squares is maintained. The three-digit numbers on the strips indicate the wavelength



of the light (in nanometers). The two-digit numbers on the lines which cross the strips reproduce the value of the x-coordinates from the CIE diagram. Actually there should be a decimal point in front of them, but it has gotten lost in this reproduction (and in MacAdam's original, too!). If the strips are joined so that their edges are "bonded" together, the undulating surface will be created. The curves we see on it trace the locations at which the values for x and y from the CIE diagram remain constant.

The transformation leading from squares to strips had its origin in so-called "MacAdam ellipses." These ellipses can be placed around the base colors specified in the CIE diagram to indicate their area of tolerance. These should be seen as nothing else but the nominal color. The ellipses, determined experimentally, delineate the positions at which

those colors lie, at which they can be distinguished from the nominal color. There is indeed no analytical term to apply to these threshold ellipses, but MacAdam gave a graphic representation of so-called "ellipse constants." These are applied to the squares taken from the CIE diagram in order to transform them into the rectangles of similar sensitivity which we can see more or less smoothed out in the illustration.

The objective of all these distortions and constructions is to obtain information about our sensitivity to differences in color. Douglas L. MacAdam was the pioneer in these investigations. In 1981, in his book *Color Measurement,* he concerned himself with the basics of color difference: "analogous to Mercator charts and other kinds of maps of the world that misrepresent the ratios of distances, the chromaticity diagram does not represent perceptually equal color differences by equal distances between points that represent equally luminous colors. The noticeability of color differences was not considered—very few data were available—when the chromaticity diagram was devised and adopted. However, as soon as it came into use, anomalies were encountered in interpreting the configurations of points on the diagram. Inconsistencies between distances and perceived magnitudes of color differences were evident. The analogy with geographical maps was quickly noted and suggestions were made to change the representation so that equal distances would represent equally noticeable color differences. The hoped-for chromaticity diagram with such properties came to be called "uniform." The search for it has extended over fifty years and seems no nearer its goal than at the beginning. Much of the accumulated evidence indicates that the goal is unattainable—that a flat diagram

cannot represent equal color differences by equal distances any more than a flat map of the world can represent equal geographical distances by equal distances on the map."

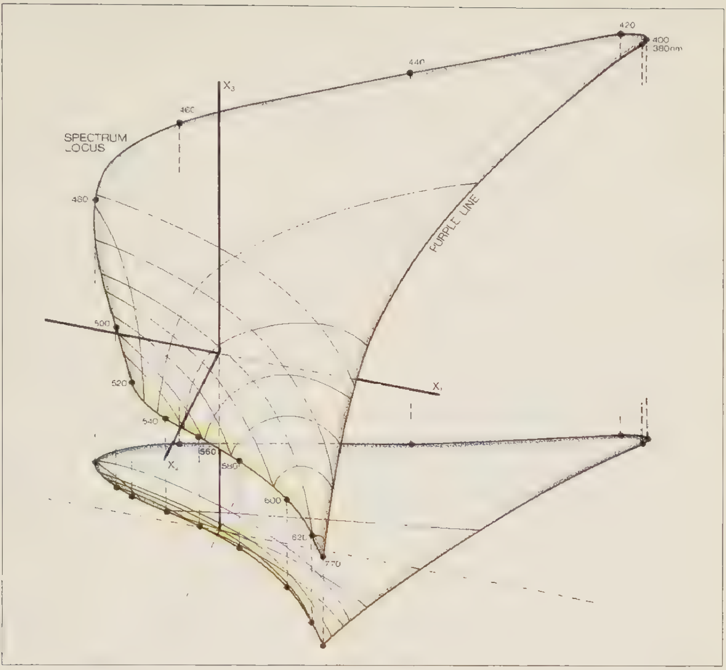
A Latin proverb—"In magnis rebus voluisse satis es"—tells us that it is enough to have merely desired great things. MacAdam wanted something great. He may have failed, but his failure was grandiose. He created something beautiful.

39 CIE—WALTER S. STILES

There have been many attempts at constructing a "visually homogeneous color space" by means of either linear or non-linear transformations of the CIE diagram (Chapter 35). However, as we pointed out in Chapter 38, these have never been successful.

The problem lies in what the experts call the metric of color space, which up to now could never claim to apply generally. The word "metric" is usually understood in connection with the stanza or rhythm of verse, which are both concerned with units of measurement. But a metric in geometry requires a unit (e.g., the meter) to measure a space, and the theoretical construction which achieves this is called a "tensor" or a line-element. This line-element also provides a mathematical way to arrive at differences in color (for example, the difference in brightness of colors with varying hues).

A metric in color space should therefore describe the variation of color induced by any two elements from the three-dimensional diversity of colors, as perceived in the eye of an observer (under set conditions of observation). In spite of the apparent simplicity of this task, its implementation is by no means straightforward. The shapes of the curves followed by the line-elements reflect numerous measurements, complex assumptions, and physical laws, and it is impossible here even to begin to explain all the associated mathematical and geometric intricacies. It is enough just to



find the resultant color solids aesthetically pleasing. An example is the figure, based on a line-element first proposed by the American Walter S. Stiles in 1946.

The idea of line-elements goes back to Hermann von Helmholtz (Chapter 18), who had attempted to formulate mathematically the perceivable differences between additive color mixtures. Within a color space, Helmholtz required all apparently identical or similar colors to be equidistant, and constructed his line-element with this in mind. Walter S. Stiles then modified Helmholtz's proposals, in order to account better for available observations of threshold values. In the description of MacAdam's system (Chapter 38), examples of these values have already been introduced in the form of the threshold ellipses which bear his name. By means of a non-linear transformation suggested by

D. Farnsworth in 1957, these regions of color-sensation tolerance could be converted into circles. Also in this illustration is depicted a similarly distorted outline of the CIE diagram, with the *spectrum locus* and the purple line still recognizable. A total of twenty-five small circles can be seen—the twenty-five representative nominal colors for which MacAdam experimentally obtained his threshold ellipses.

The purple line and the position of the spectral colors calculated using the Stiles line-element can also be seen on the UCS surface. The coordinates have been selected in such a way that the standard light source 'C' used in the CIE diagram is located at the zero point of the new system of coordinates X1, X2, and X3. At the same time, the projection of the UCS surface according to Stiles can be seen in the plane formed by X1 and X2.

With this chapter and the preceding system, we have left the region once referred to by the physicist Erwin Schrödinger—due to its basis on the assessment of color similarity—as the "terrain of lower colorimetry." MacAdam and Stiles are more concerned with the equidistance of colors, which in principle has little to do with their similarity, and here we therefore speak of "higher colorimetry."

40 FABER BIRREN

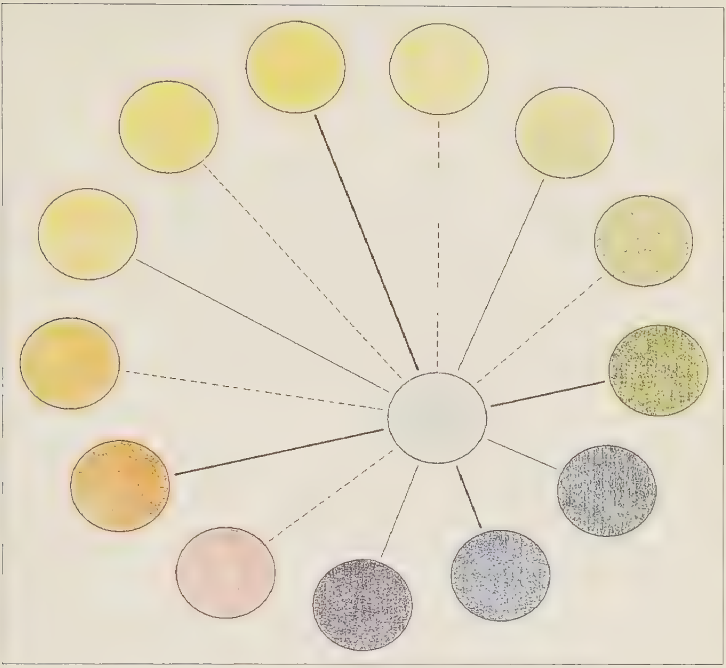
The American Faber Birren (1900–1988) probably wrote more books on color than anyone else ever—some twenty-five. His first, *Color in Vision,* was published in 1928, and his final major work, *The History of Color in Painting,* appeared in 1981. In 1934, Birren produced two works, *Color Dimension* and *The Printer's Art of Color,* in which he introduced his own color system. This he described as a "Rational Color Circle," which grouped 13 colors around a gray which did not itself appear at the center. The circle's colors are yellow, yellow-leaf green, green-leaf green, green, turquoise, blue, violet, red-violet, red, red-orange, orange, and orange-red. The thickly drawn lines accentuate the psychological primary colors attributable to Hering (Chapter 22), the dotted lines refer to mixtures, and the thinly drawn continuous lines represent secondary colors. Birren explained his color circle in accordance with the practicalities of art and artists. First, he differentiated between warm and cold colors. Birren's warm colors began just to the violet side of red, extending beyond yellow. If a color circle is constructed using the three subtractive primaries, yellow, blue, and red, placed at equal distances, the warm colors will occupy about half the circle. If, on the other hand, a color circle is constructed using the four psychological and visual primary colors, yellow, green, blue, and red, the warm colors will be suppressed and will occupy less than half of the circumference.

Most artists, in fact, emphasize the warm colors more than the cold because—according to Birren—their effect is more dynamic and intense. The eye can, in fact, distinguish more warm colors than cold ones, and Birren justified the arrangement shown as follows, "If we were to create a rational color circle, with satisfyingly arranged, easily distinguishable steps around its circumference, such a color circle would contain more warm than cold color hues, even if the central point of complementation were to be thrown out of equilibrium as a result."

The expression "point of complementation" points to the fact that the usual color circles become gray to the eye when they are rotated about their central point, which thus becomes the point of complementation. Birren's color circle does not become gray when rotated around its center.

In 1937, Birren introduced the triangular arrangements to incorporate and display the visual and psychological relationships of colors. The seven names summarize the ways in which we can experience colors. Pure color combines with white to produce a "tint." At the same time, the words "shade" or "tone" come to mind. Shade implies a dark color, produced by tempering with black, and a tone is the result of combining a pure color with a mixture of black and white.

In the second triangle, Birren has placed pairs of numbers separated by a decimal point. The digits preceding the decimal point relate to the proportion of white, which can range between 100 and 0, thus a percentage. Similarly, the digits after the point indicate the percentage of black. The proportion of color can be calculated by adding both achromatic numbers and subtracting the result from 100. Thus, the combination 0.0 will be pure color;



10.50 indicates a color hue containing 10% white and 50% black, and thus 40% pure color.

The color triangle represents an attempt by Birren to reveal a harmony of colors. According to his ideas, harmony can always be found by following the connecting straight lines, in other words white-gray-black, or color-shade-black. Birren thus endorsed a generally held view that beauty is the result of good ordering of colors.

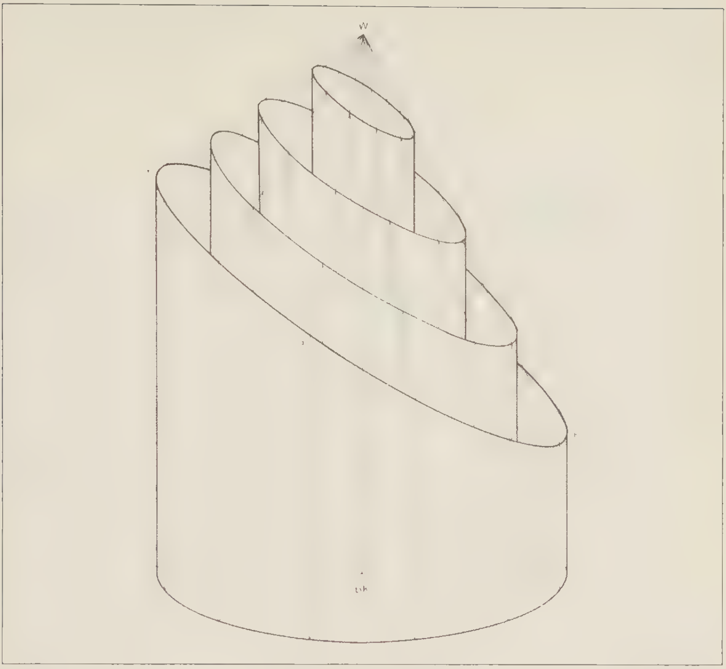
41 TRYGGVE JOHANSSON

During Hering's research on sensory perception in the late 19th century (Chapter 22), he required that the concepts employed—for example, color itself—be derived solely by means of perception, in order to avoid any confusion with their physical or physiological causes. This implied a complete absence of any classification based on data from the field where the stimulus originated for a particular sensation. In the area of color, this—for Hering self-evident—principle has, of course, been subjected to constant violation; many color systems have been created under consideration of aspects from both chemistry and physics.

During the 1930s, Tryggve Johansson (1905–1960) adopted Hering's ideas and sought to promote them in his own country, Sweden. He suggested the color solid shown here, rising above a circle divided into four equal parts—the color quadrants—in which, as his fundamental colors, yellow (Y), green (G), blue (B), and red (R) are placed.

In his system, dating from 1937, Johansson portrayed white as a point at the tip of his construction, while black (BK) is not given a fixed position, instead being placed at the lower boundary of each color to occupy the entire base of the color solid. We show vertical sections through the solid, with the lines in each case showing—from above downward—how all the colors (C) of equal brightness, equal saturation, equal brilliance, and equal intensity are situated in this system.

Later, Johansson also utilized A. H. Munsell's ideas (Chapter 29) and replaced Hering's "degree of black" with



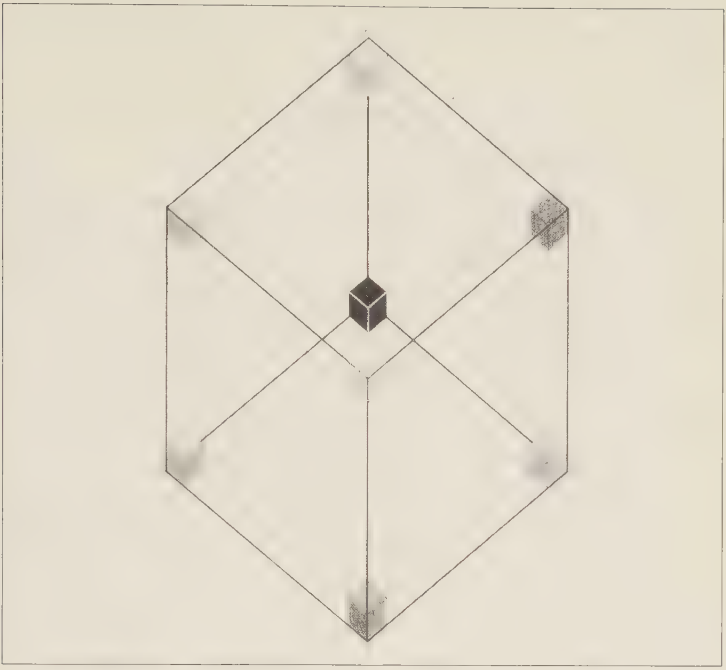
a brightness variable reminiscent of Munsell's value, supplementing this with a further parameter, that of "clarity," which points to the "degree of darkness," later to be used in the DIN system (Chapter 45). Johansson's system became very popular, finding wide appeal among teachers, architects, and designers.

AEMILIUS MÜLLER

There is little in the early life of the Swiss economics graduate Aemilius Müller (1901–1989) to indicate any serious interest in colors. After studying economics, he went on to become, in turn, an advertising manager, a graphic designer, and a journalist. In 1941, however, he chanced upon an old copy of Wilhelm Ostwald's color theory (Chapter 30), and thus stumbled upon a new aim in life—the creation and publication of a method for dealing with colors, based on Ostwald's ideas.

By 1944, he had already published his *Swiss Color Sample Card,* and in 1948 the first edition of his *Modern Theory of Color Harmony* appeared, with color in architecture as its theme. Müller pointed out that the gradations of color hue, often appearing monotonous, can be made more attractive by allowing them systematic deviations, although at the same time so-called "color inversions" should be avoided.

What did this newly-coined term mean? Both in the spectrum and in the color circle, each color has a specific luminance, yellow being the brightest, and blue the darkest color. According to Müller, color combinations can only appear harmonious if the relationship between their brightnesses corresponds to the natural brightness relationship between these particular colors. Reverse the situation and there will be an inversion, as well as discord. The Three-Color Cube 1000 shown following was introduced by Müller in 1951. The original version comprised 10 plates of 100 colors each, with each plate demonstrating the



systematic mixing of colors important for the printing industry.

Müller's cube was based on proposals from Max Becke (Chapter 32), and—like all color cubes—it graphically shows the mixtures possible using three basic colors. For subtractive color mixing, the eight corners are occupied with: three primary colors—yellow (60), magenta (20), and cyan blue (40); three secondary colors—red (10), blue violet (30), and green (50); and the achromatic colors white and black. The illustrations reproduce some stabilizing links within the cube and at the same time accentuate its geometry.

The Three-Color Cube 1000 is itself based on the basic colors normally encountered in three-color printing—yellow, bluish red (magenta or purple), and greenish blue

(cyan blue). It represents a system of mixing color which clarifies those colors arising if three transparent layers of the subtractive basic colors are superimposed at varying levels of saturation.

Ostwald had based his concept for color on the double cone, which Müller also adopted and improved. His color circle incorporated the already familiar double set of three plus three basic colors, with the color hues spaced at intervals perceived as being equidistant. Their numbering—clockwise from 1 to 60—is graphically clear and reminiscent of the accustomed 60 divisions of a clocks's face.

By taking vertical radial sections 60 possible triangles of equal color hues can be extracted from the double cone, with white, black and the corresponding full color located at the three corners. The ten numbered gradations along the side of each triangle are co-ordinates, revealing the proportions of the three variables. The result of Müller's efforts—the famous *Swiss Color Atlas,* first published in 1962—contains a total of 2541 color fields.

Like the great Ostwald before him, Müller strove toward *The aestethics of color in natural harmonies,* the title of a major work he brought out in 1973. A collection of 200 color tables, it was intended to reveal the fundamental relationships of colors. Werner Spillmann, a lecturer on color design in Winterthur, Müller's home town in Switzerland, praised this work a "collection of highly refined color studies", pointing out that "The basic theme of this collection of color charts is to show the possibilities for linking the contrasting elements of a compilation of colors. The tables provide rich and impressive solutions for this problematic area—solutions, which, visually, can always be directly experienced and understood. The creator of this

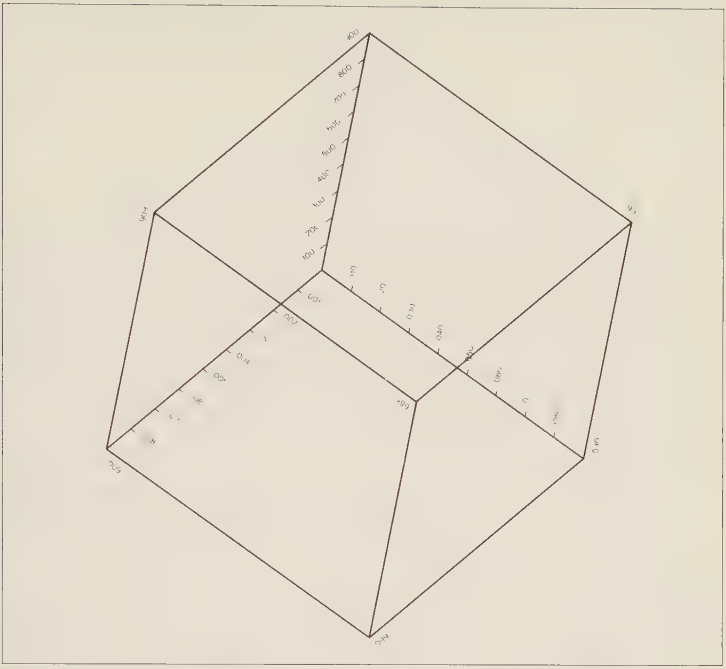
singular work makes no secret of the laws on which he has based it. On the contrary, he has attempted to reveal the simplicity from which such pleasant sounding color combinations can arise." Anyone wanting to deepen his appreciation of art through a more thorough grasp of color has come to the right place with Aemilius Müller.

43 ALFRED HICKETHIER

Alfred Hickethier proposed his cube-based system of colors in 1952. The Hickethier cube was constructed on the same principle, having been developed primarily for practical applications in three-color printing and three-layer color photography. Three printing inks were selected with particular care for the creation of the primary colors: yellow (900), magenta red (090), and cyan blue (009). These are positioned as primary colors in three corners of the cube. Three of the remaining five corners are occupied by secondary colors: red (990), violet blue (099), and green (909), and the two extremes by black (999) and white (000). The series of achromatic colors (grays) runs diagonally through the color solid. Together with the three secondary corner points, the three primary corner points form two opposing equilateral triangles. Viewed obliquely from above, the cube reveals an arrangement which corresponds to a color circle with six colors.

The three primary colors have been selected for their high degree of saturation and are perceived as lying approximately equidistant from each other. With the three numbered grids shown, Hickethier produced a ten-part color series from each basic color to white. Each series runs from its basic color through to printing-paper white, in gradation steps perceived as being nearly equal. With white identified as 000, the three basic colors are reached via 100 and 200 through to yellow (900), via 010 and 020 to magenta red (090), and finally via 001 and 002 to cyan blue (009).

By superimposed printing of the colors, 10 x 10 x 10 = 1000 standard colors will be created from the overlaps of



these basic series. Identification of color mixtures is achieved by putting the three-digit numbers of their component parts together. For example, if the colors 700, 030, and 004, respectively from the yellow, magenta-red, and cyan blue series, are printed on top of each other, a mixed color with the three-digit number 734 will be formed. If three colors of the same gradation—for example, 300, 030, and 003—are printed, a near-gray will result.

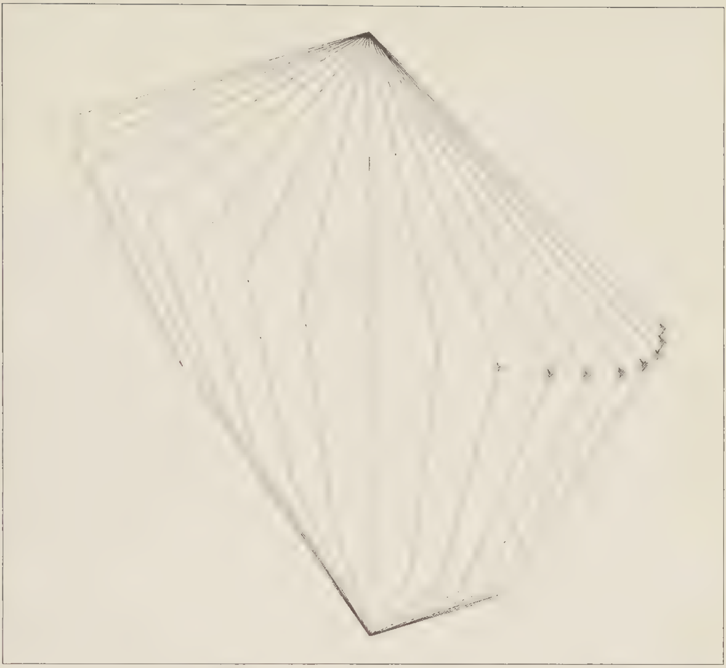
The first Hickethier Color System was printed in 1952, using the dot matrix system. Twenty years later, an improved edition appeared, produced by superimposing three color layers. In spite of the apparent clarity of the aids to formulation that they incorporate, these systems are of little practical use when alternative coloring materials to the stipulated pigments and dyes are employed.

44 SVEN HESSELGREN

In 1953, the Swede Sven Hesselgren published his *Color Atlas* with the intention of giving tangible forms to Tryggve Johansson's color solid (Chapter 41). In Hesselgren's *Color Atlas,* 507 standard colors were specified, arranged in planes of equal hue according to brightness and saturation. The purpose of presenting these colors was to provide the structure for a phenomenologically based color system. Hesselgren's observations not only contributed to the future NCS system (Chapter 51), they have also assisted in the development of color charts for use by architects and other professionals involved in interior and exterior design.

A 24-part full-color circle formed the basis of Hesselgren's atlas. Its full colors were selected to contain the four basic colors of yellow, red, blue, and green attributable to Ewald Hering; these, more than any other colors, are psychologically perceived as being independent (Chapter 22). Thus, yellow appears neither reddish nor greenish, red neither yellowish nor bluish, blue neither reddish nor greenish, and green neither bluish nor yellowish.

These four basic colors divided the circle into four quadrants, which in turn were subdivided into gradations perceived as being equidistant. Five hues were placed between yellow and red, seven between red and blue, three between blue and green, and three between green and yellow. So, initially, 22 colors completed the circle. For practical reasons, a greenish blue and a greenish yellow hue were also inserted—to bring the total number to 24.



The order of colors basically conformed to hue, saturation, and brightness. In addition, two further parameters—intensity or color strength, and clarity or veiling—were specified, which, together with the three basic parameters, were viewed by Hesselgren as both necessary and sufficient to describe each color in all its possible variations.

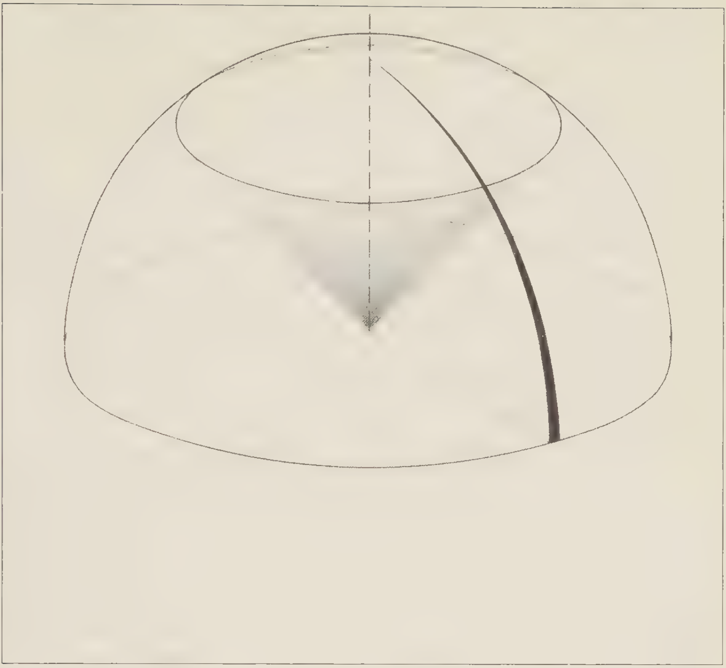
For Hesselgren, colors of the same saturation did not lie on the surface of cylinders arranged about an axis, but once again could be found on a series of concentric cones with black at their common tip.

45 DIN SYSTEM

During the 1930s, the Deutsche Institut für Normung (German Standards Institute), abbreviated DIN, recognized the need for a new color system more practical than the Ostwald system (Chapter 30), which had been in use since the First World War. Manfred Richter, a staff member at the Bundesanstalt für Materialprüfung (Federal Institute for Materials Testing), was assigned this task. He was requested to proceed on a scientific basis with the aim of creating a new system capable of standardization. It was not until 1953 that Richter and his workers were finally able to submit their results.

The first question to be resolved concerned suitable color coordinates. The objective was, as effectively as possible, to fulfill Ostwald's original requirement—which, incidentally, he himself had failed to do—of basing the new system on a series for each variable perceived by an observer as having visually equidistant steps. In order to divide up the full color circle into perceived steps of equal size, extensive experiments were carried out using many hundreds of test subjects and over a hundred color hues. Color coordinates were derived for 24 points, which defined the "equidistant" color hues. Numbering commenced at yellow (1), proceeding via red (7), blue (16), and green (22), to return to yellow. The next step was to arrange colors of the same saturation and brightness within a given circle.

The DIN system still operates today using three variables: DIN color hue (T), DIN saturation (S), and DIN



darkness (D). They provide the coordinates for the three-dimensional system of non-self-illuminating colors. This diagram, at left, uses the visible half-plane to display surfaces of constant T-value, surfaces of the same S-value are represented by the cone, and surfaces of the same D-value are shown by means of the sphere. Within the DIN system, the intersection of these three surfaces determines a color. We show the three-dimensional system which makes possible the DIN color chart, and another figure shows a representative surface of equal color hue from the system. The darkness scale runs from above downward—the numbers on the axes define either the reflection of light or the brightness—and the saturation values are given on the horizontal axis.

The darkness gradation applicable to all color series is based on a rather baffling formula for the gray series, defined in such a way that ideal black is assigned the darkness gradation 10 and ideal white (and all optimal colors) 0. It is mainly this parameter which distinguishes the DIN color system from the Munsell system (Chapter 29) and enables the DIN system to associate colors, not of the same brightness but of the same relative brightness. In terms of perception, this is more appropriate, since we tend to sense colors of differing color hue as being of equal value.

A DIN color hue is defined (at a given level of saturation and darkness) by means of a color circle with 24 gradations, which was established by the selection process described above. Here, we can see that colors of the same hue are characterized by a so-called dominant wavelength, which can also be found in the CIE diagram (Chapter 35) by drawing a straight line from the so-called achromatic point of the standard light source 'C' through the color and then 'noting the point of intersection with the surrounding tongue-shaped curve. The way in which the DIN system determines not only the color hue but also saturation is in principle no different than for any other system. With the DIN color circle, saturation gradations commence with S = 6 and end at an achromatic point S = 0; and together, color hue and saturation form the color type. As already mentioned, the DIN system achieves special status thanks to its darkness scale, which can be regarded as the measure of the relative brightness of non-self-illuminating colors. The introduction of this very complex measurement was intended to provide psychological balance to the DIN color circle, also with regard to brightness. This does not necessitate there being a sensation of equal brightness for all

colors in the color circle, merely a visual impression that they belong together.

The inclusion of samples was always planned for the DIN system, and a satisfactory version of 600 color samples was produced between 1961 and 1962—the DIN Color Chart 6164. It comprises small color rectangles of 20 x 28 mm., the colors of which are identified by a three-figure digit in the sequence T:S:D. A green, therefore, may be identified as 22,5:3,2:1,7. (Note that in German, a comma is used to signify the decimal point.)

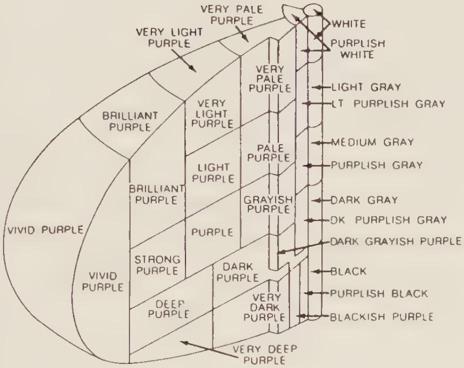
The DIN system presented here is the only system to fulfill the four requirements that its creator, Manfred Richter, demanded as a basic principle of any color system. They stem from the observation that no system can be based on color sensations because any color atlas must depend on color samples which represent particular color valencies. Richter states in his *Introduction to Colorimetry,* "First and foremost, any system using a color atlas should be based exclusively on color valency, and not on pigments and dyes. Secondly, the selected colors should be numerically exactly defined. Thirdly, the colors should be selected so that, displayed in a non-empirical system, they will result in smooth curves and surfaces. Fourthly, a certain built-in tolerance of reasonable latitude should be both specified for all color samples and complied with." This last point was included because excessively narrow tolerances would send the price of sample manufacture skyrocketing. Beauty may have its price, but there must always be someone who can pay for it.

ISCC—NBS SYSTEM

Colors must have names, and it is a justifiable assumption that linguistic color identification itself can be the foundation of a color system. Between 1955 and 1976, the Americans K. L. Kelly and Deane B. Judd took this route to create a color system, reducing colors to increasingly fine blocks and then filling these blocks with equally finely defined terms for colors. The illustration shows this block separation—here for the purple segment—commissioned by the Inter-Society Color Council (ISCC) for the National Bureau of Standards (NBS) in Washington. The adjectives used in this particular example are the same for all other colors: vivid, brilliant, strong, deep, light, dark, and pale. Note that the terms "light" and "dark" are only used near the neutral black-white axis, and not in regions of high saturation.

Kelly and Judd used the three parameters of hue, value, and chroma to define the color blocks which subdivide their color solid, just as the American A. H. Munsell had done (Chapter 29) at the beginning of this century. The actual color names have been selected independently from Munsell's system).

The descriptive terms chosen for the various segments chiefly show the subjective variables of the phenomenon of color which emerge when a color is held in front of the eye for an extended period of time. It is evident that Munsell's red gradation, classified as R4/14 is identified as being just as "vivid" as the corresponding ultramarine blue, although



they were both certainly of varying brightness. Vividness is obviously assessed as a significant parameter, alongside depth, strength, and brilliance.

Any attempt at ordering colors according to language must be viewed skeptically when neither the ambient conditions of observation nor the experiences of the observer can be taken into account. It is therefore no surprise that the generic system shown here has achieved little recognition. Naturally, the link between language and color not only awakened the interest of colorimetry experts, but also attracted the attention of linguists and philosophers of language, a fundamental question being whether it is thought that determines language, or the reverse. Any answer will depend on the feasibility of observing language and speech as separate entities. Of prime importance here,

however, would be to obtain data on thought that is uninfluenced by speech. This could be achieved in the case of colors, because we can examine how a human being divides up the spectrum of a prism without having to ask him how he is doing this, and therefore without resorting to language. Additionally, we can see if different languages apportion the visible spectrum in different ways. Since the 1950s, linguists have occupied themselves with this question, the present consensus being that our perception gives the spectrum its structure, not our language. Language only duplicates—more or less completely—the differences set by our universal perception. Besides, our recognition of a color does not depend on whether we have a descriptive word for it.

Another interesting discovery was made during these investigations. The two American linguists Brent Berlin and Paul Kay established that not all languages possess the same number of basic color names. A short word which was neither further separable nor in use as a description of a material was accepted as being a basic name. Yellow and green thus count as basic names, but not dark yellow or turquoise. Of almost one hundred different languages investigated, none had less than two nor more than eleven such basic names.

More exact evaluation reveals how the corresponding color vocabulary of a language appears to conform to a certain sequence. If a language only has two color words, these will be black (or dark) and white (or bright). Red will always be the first chromatic word to be found in addition to these two. The fourth basic name is then either green or yellow, and a language with five expressions for color exhibits the sequence black, white, red, green, and yellow. Blue appears only in sixth place, with brown seventh. Up

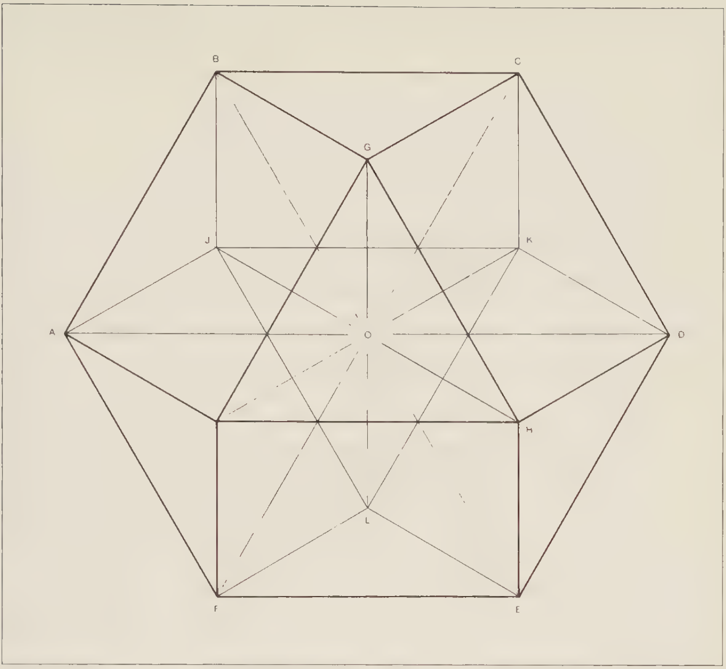
to this point, there has been a specific hierarchy; beyond it, color vocabulary is supplemented by the quartet of violet, orange, pink, and gray in an arbitrary order.

Paul Ray suspected that with this structure of vocabulary a sequence became visible which conforms to the way in which humanity built up color terms. Although red was not necessarily the first color seen by our ancestors, the color of blood could well have been the most important color with regard to our survival. Given the excitement and reaction which red can still evoke, perhaps this idea should not be easily ignored.

47 OSA SYSTEM

If all eight corners are sliced off a cube down to the midpoint of each edge, the resulting solid is what mathematicians call a cube-octahedron. It has twelve corner points equidistant from the center. A color system based on such a structure was presented in 1960 by the Optical Society of America. In fact, it was the Committee for Uniform Color Scales (UCS), founded in 1947 under the chairmanship of Deane B. Judd, which had completed this task and proposed this unusual geometry. So when the OSA-UCS system is referred to, the regular lattice of a cube-octahedron is actually meant. The corner points are labeled alphabetically, and the center is given a value of zero. Such a structure permits the allocation of twelve closest neighbors to the central point, as in the small cube-octahedron seen above.

The OSA color system is different from all systems introduced so far. As we know, colors can be determined by three independent parameters—in the DIN system (Chapter 45) these are color hue, saturation, and darkness; with the Munsell system (Chapter 29) they are chroma, hue, and value. With all systems examined up to this point, each of these parameters has been evaluated using a scale independent of the values of the other two. The colors of the cube-octahedron, on the other hand, are chosen so that everywhere in the lattice the distances between a color sample and each of its twelve nearest neighbors represent color differences which are perceptually equidistant, i.e. perceived as being



the same. Thus, if we draw a line in each of the six directions determined by the lattice structure, linearly graded scales for color difference will be produced. The position of a sample within this lattice is defined by the coordinates of three axes all intersecting at right angles, specified by the UCS committee as being lightness (L), yellowness-blueness (J, abbreviated from the French *jaune*), and greenness-redness (G). These unusual names should not be taken too literally. The reference J represents yellow at a high lightness value (L), but without representing the yellow-blue axis. For negative values of J, the axis separates blue from the violet region. Similarly, a positive value for G will not indicate green. Instead, this parameter separates the blue and green colors; red does not lie at the end of the negative G scale, but pink. It is best to treat G and J as abstract parameters

which, in the first analysis, have nothing to do with colors. They were originally introduced to serve also as decimal numbers defining the positions of the color samples. In the 1978 report issued by the Committee on Uniform Spacing, a total of 558 samples were colorimetrically specified, together with their exact coordinates.

The variable L (lightness) is of note for two reasons. Not only is it constructed in such a way that it incorporates both chromatic and achromatic colors, but its value will be zero when the brightness corresponds to that of the background generally recommended for viewing the samples. Positive values of L imply a color brighter than the background, and negative values a color which is darker. Since the remaining two parameters are intended to represent variables of opponent-colors, they will assume zero values all along the neutral axis.

The center of the figure has the trio of digits 0,0,0, and is so furnished to correspond to the neutral gray of the Munsell scale (N5).

The OSA-UCS system allows the scientist to analyze color differences and lets both designers and artists select various color harmonies, simply by extracting suitable sections from the color solid. Despite its fascination, many professionals evidently prefer other, less involved systems, finding them more clear.

48 NCS SYSTEM

The Natural Color System, or NCS, originated in Sweden. It operates with the six primary colors proposed by Leonardo da Vinci, using Ewald Hering's opponent theory (Chapter 22). Preliminary research work also employed Tryggve Johansson's system (Chapter 41) and Sven Hesselgren's color atlas (Chapter 44) as precise references. The results of the project, initiated in 1964, were presented by Anders Hård and Lars Sivik toward the end of the same decade.

Their objective was to establish a color system which anyone with normal color vision could use to determine colors, without needing color measuring instruments or color samples. The NCS system was designed to serve as an aid in defining the color of the walls in a room, a distant tree, a painted surface exhibiting simultaneous contrast, or a point on a television screen—based solely on perception, without involving "color matching," the mutual comparison of a series of colors.

The external shape of the Natural Color System was a double cone, so constructed that the four basic psychological colors, yellow (Y), red (R), blue (B), and green (G), occupied the circular base, taking up evenly spaced positions. The tips of the double cone were black and white, and an equilateral triangle was formed by connecting each of the four basic colors to these two achromatic tips.

This triangle specifies the tints of a color. The perceived proportions of black (S), white (W), and color (C) are shown. The color positioned at the outermost point on the

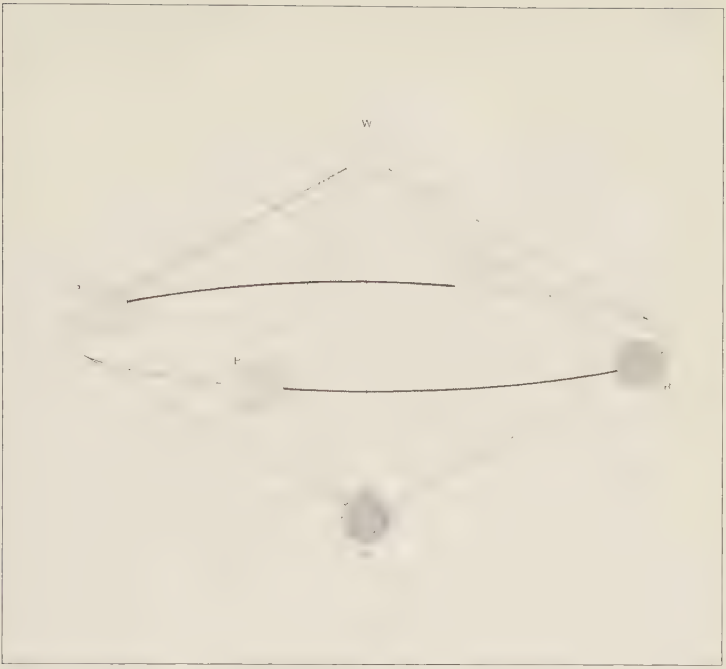
right can then be identified using the parameters S = 10, W = 10, and C = 80 (with the three numbers always totaling 100).

With the NCS color circle, each of the quadrants is partitioned among two basic colors by a scale which expresses the portion of each color as a percentage: Y40R implies a yellow with 40% red, and B20G implies a blue with 20% green. This allocation is based on the principle of similarity, which states that each color is similar to a maximum of two chromatic elementary colors (in addition to black and white), and that such a match can be quantitatively assessed down to an accuracy of 5% (without referring to a physical standard). Such estimations should be feasible for observers with little experience in dealing with colors.

All variables in the NCS system are likewise defined using similarity. Color hue is expressed as just described. An orange with the coordinates Y30R, would have a 30% similarity to red and a 70% similarity to yellow.

The other variables are the proportion of a chromatic color (chromaticity, C) and proportion of black (S), and these are also entered into the triangle. All colors lying on the vertical lines—parallel to the black-white axis—contain identical chromatic proportions. In the same way, all colors in the rows running parallel to the line between white and the observed color contain the same proportions of black. And finally, all colors in the rows running parallel to the line between black and the observed color contain the same proportions of white. (Since this is evident from the intersection of rows C and S, it is not explicitly shown).

By being restricted to the descriptiveness of a color sensation, the Natural Color System succeeded in adopting the positive aspects from Munsell (Chapter 29) and Ostwald



(Chapter 30) without importing any of their disadvantages. Its creators demonstrated empirically that any perceived color surface could be described by quantifying its similarity to four of the six elementary color sensations, and they adhered to this strict phenomenological approach (see Chapter 41).

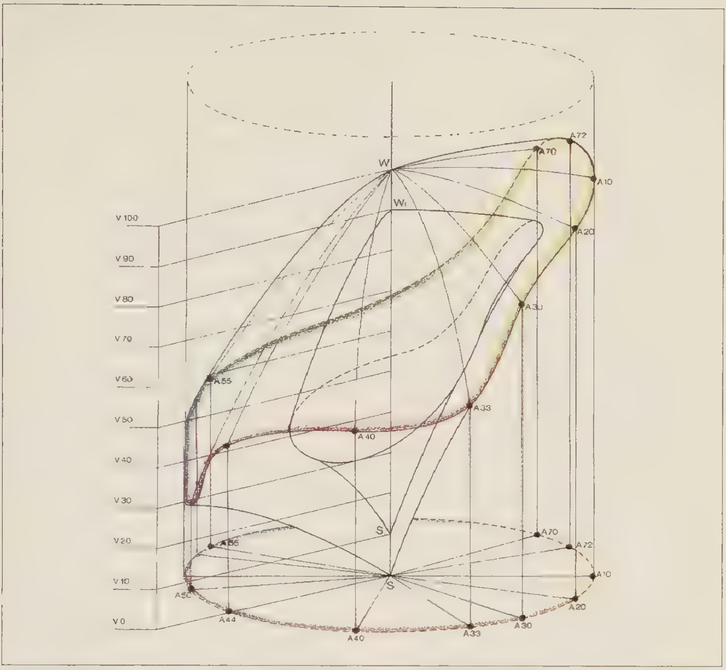
Of course, the Natural Color System is not complete. Its extension into the realm of translucent colors, for example, would increase our knowledge both of our visual system and of perception. The boundless diversity of colors exceeds the limits of every closed system, even when constructed in such a refined and well-considered way.

49 COLOROID SYSTEM

The Coloroid color system was developed at Budapest Technical University, between 1962 and 1974, under the guidance of Antal Nemcsics. The aim was to provide both a technical and an artistic aid to architects involved in environmental color design, since according to its Hungarian inventor, no contemporary color systems fulfilled the requirements of color planning. So a new color space was developed, employing "psychometric scales based on the selections of some 70,000 test persons," as Nemcsics reported in 1978. A multitude of people thus helped clear the way for the Coloroid system, which is based on "aesthetically uniform" series of colors. Uniform aesthetic spacing, the guiding principle behind this construction, calls for a phenomenological equilibrium for all color scales within the system, with perceived differences being only of secondary importance.

Color hue (abbreviated A), saturation (T), and brightness (V) emerged as the variables in the Coloroid system. In line with other color systems based on perception, the entire three-dimensional range of colors was arranged on the inside of a cylinder.

The colors of the spectrum and the purple line are distributed around the axis of the cylinder. To be more precise, they are located around an approximately elliptical, inclined section through the three-dimensional construction. They represent the so-called Coloroid limit colors. The system's basic colors are selected from these—a total of



48 colors in all. These colors are identified by whole numbers and lie "at distances perceived as being almost aesthetically uniform."

The aesthetic uniformity of the scale for color hue was essentially achieved by asking test subjects to create a color circle from 160 color samples—differing color hues at Munsell brightness and chroma V/C=6/12 (see Chapter 29)—in such a way that the continuous scale appeared to change uniformly when viewed as a whole.

Each limit color in the Coloroid system is linked to black and white by a so-called limit curve. A closed color space is thus created which contains all sensations of color within an arrangement corresponding to the perceived characteristic values of the system. A (smaller) Coloroid color solid, containing colors of lesser brightness and saturation, is

located within this Coloroid space. The extremes of red (beyond 700 nm.) and violet (below 450 nm.) are not included in its color hues. In the outer solid, brightness increases along the scale from black to white in 100 uniform gradations, which were more accurately defined by the system's authors as the square root of luminosity. Saturation, also divided into 100 units, was defined by analysis of the test color as an additive mixture of the spectral colors (or purple). The saturation of a color is given as the percentage content of the spectral color (or purple) present in the mixture.

In the Coloroid planes, the half-plane sections are shown with the color solid. The surface color limit-curves also appear in this diagram. The color hue or characteristic wavelength of every color in the same plane is the same.

It is possible to describe and detail the exact relationship between this system and the Standard Valency System (the CIE diagram, Chapter 35), but we will not attempt to do this.

The Coloroid system introduced the expression "aesthetically uniform color space" for the first time. A scale is regarded as being aesthetically uniform when it appears to an observer as complete and also exhibits gradual change. The idea behind this construction becomes clear if one realizes that, when planning a colored environment, a harmony must be created for colors of very different hue, saturation, and brightness. For the designer, aesthetic uniformity is more important than being able to register accurately any small differences in color or to reproduce them. He is not so much interested in actual differences between colors as in their harmonious interplay, and the Coloroid system offers a way of achieving this harmony.

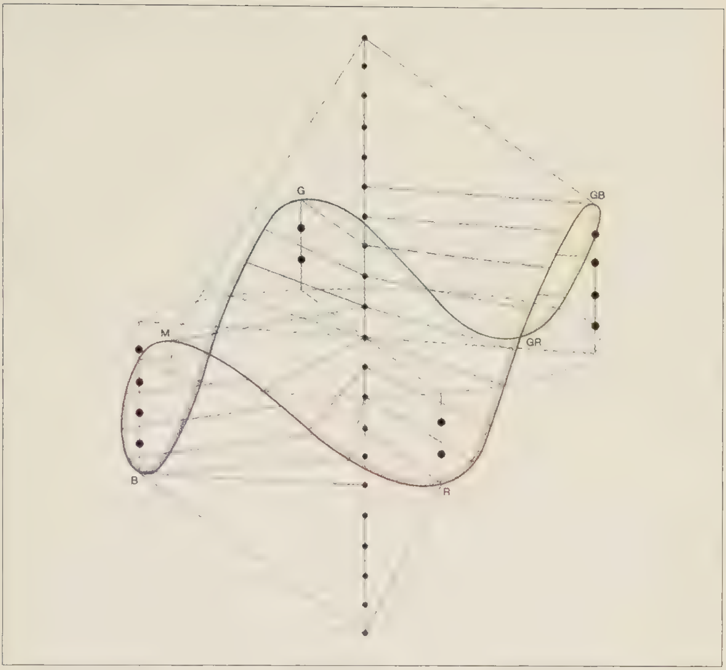
50 J. FRANS GERRITSEN

In 1975, the Dutchman J. Frans Gerritsen made a fresh attempt at arranging colors according to the laws of color perception. He selected three variables—color hue, brightness, and saturation—and, as in the Coloroid system (Chapter 49), organized them within a cylinder. On the wall of the cylinder we can see an irregular wavy line, formed by color hues arranged in a circle at alternating higher or lower levels of brightness.

The color circle comprises six so-called full colors identified by Gerritsen as yellow, red, magenta, blue, cyan, and green. He arranged them in such a way that complementary pairs lie diametrically opposite each other, with three brighter colors alternating with three darker colors. All conceivable primary and secondary colors could thus be placed both on the cylinder wall and on the wavy line. Gerritsen identified the achromatic colors running from white via all the gray tones to black as tertiary colors. These form the color cylinder's brightness axis, with graduations A to J. We show vertical and horizontal sections through the perceptual color space. Horizontal sections exhibit colors of the same brightness. Gerritsen sought to rediscover some old laws with his model; in his *Evolution of Color Theory* (1984) he wrote, "As with the Greeks, colors are once again arranged at individual brightness levels between black and white. Red, a 'mixed color' once believed to occur between black and white, is found here on the outer circumference

between black and white. Newton's colors of the daylight spectrum are given their rightful place. As in Maxwell's color system, the basic colors alternate—three brighter and three darker. The irregular wavy line, running around the cylinder wall and joining individual points of full-color brightness permits regular gradations of brightness and color." In addition, Gerritsen selected his system so that we can recognize the opponent-values black-white, blue-yellow, and green-red as signal transmissions within the process of color vision. Gerritsen had definite ideas about the evolution of the visual sense during human existence. At the first stage, only information about darkness or brightness could be registered, and there was just one black-white opponent-signal. As the second stage, sensitivity to the opponent-signal blue-yellow evolved from this, followed by sensitivity to the red-green opponent-signal as the third stage. Yellow is the neutral point of transition for the color-pair red-green, as is white for blue-yellow. Of course, for black-white it is gray. These ideas about the phylogenetic emergence of color sensitivity can be traced back to the physicist Erwin Schrödinger, who in 1924 had already reflected "on the origin of sensitivity curves within the eye" in order to better understand the psychology of color order. Schrödinger not only made it easier for us to grasp that white and yellow are "genuine basic perceptions"—one from the monochromatic and the other from the dichromatic stage of evolution—he also provided an explanation for red-green color blindness, the most common disturbance of normal human color vision, as being a classic atavism of the light sensitive organ, a throwback to a more primitive stage.

Today, scientists can explain color blindness from another perspective, involving genetics. Modern biology



has succeeded in identifying several genes which contribute to color vision—specifically, genes which carry the biological information for the enzymes making the color pigments in the eye which receive and relay light to the brain. Genes responsible for the blue, red, and green pigments have been located, for simplicity's sake here named the blue, red and green genes. While the blue gene is located separately from the other two color genes in the genetic material of the cells, the red and green genes are adjacent to each other. During the normal genetic mechanism of reproduction, improper mixing (abnormal "crossing over") between these adjacent genes can occur, leading to their inactivation. The probability of this occurring is increased by the surprising fact that there are numerous green genes, while there is only one copy each of the blue and red genes.

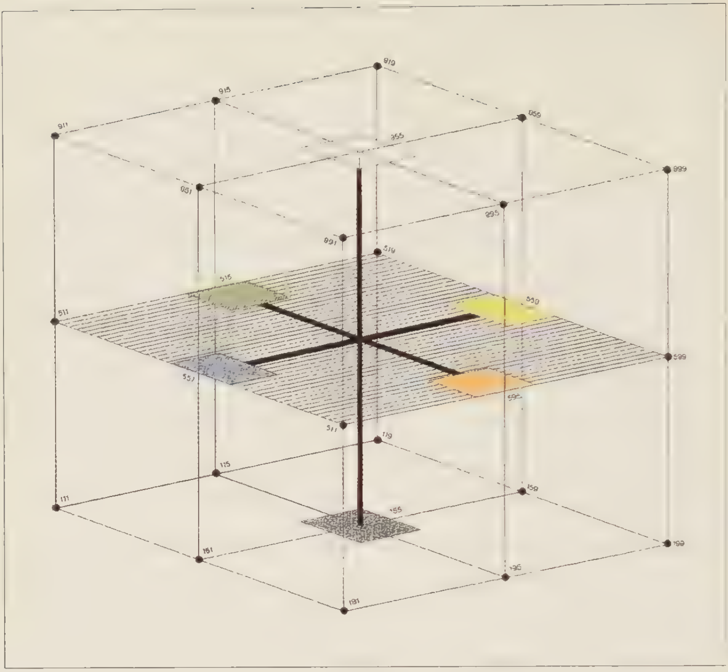
Red-green color blindness can thus be readily explained from the genetic point of view. The distribution and structure—which science can now explain in detail—of the three genes for color vision lead us to conclude that Gerritsen's interpretation of opponent-colors and their creation is compatible with the molecular facts, further implying that the polarities centered on white and yellow could also be perceptual atavisms or throwbacks.

51 CIELAB SYSTEM

Unfortunately, as critics have often pointed out, it is not possible with colorimetry's famous CIE diagram (Chapter 35) to determine color differences simply as gradations on a chart. This is most evident in the excessive representation of green, and the bunching of red, violet, and blue hues into the corners.

Since the 1960s, many proposals of simple, practicable formulae for calculating color differences have appeared in the technical literature. These have met with varying degrees of acceptance and application. In 1976, a new metric named CIELAB or CIEL*a*b* emerged, with the recommendation of the CIE. It has since found wide use for non-self-luminous objects such as textiles, paints, and plastics. The CIEL*a*b* system is apparently able to cater to the industrial needs mentioned above. The CIELUV or CIEL*U*V* system, introduced at the same time, assists in the registration of color differences experienced, for example, with photographic flashes or the television screen.

To arrive at the CIEL*a*b* color space, the three colorimetric coordinates (color values) X, Y, and Z from the CIE Standard Color Table (Chapter 35) have been transformed into three new reference values L, a, and b. In a not entirely simple way, X and Y become a, and b is created from Y and Z. Y becomes L, also by a complex procedure. L represents a type of "psychometric brightness" (or lightness), defined by the appropriate function of a psycho-physical value (a color value). This function is selected in such a way that



uniform steps on the scale will reproduce as closely as possible the uniform differences—which are related in terms of lightness—between colors. The values of L extend from 0 for black *(nero)* to 100 for white *(bianco).*

The resultant CIEL*a*b* diagram is also called the Psychometric Color Diagram. Its colors lie at right angles to each other along two axes, and the plane they create lies at right angles to the achromatic axis. The resultant three-dimensional "uniform color space" is based on the four basic psychological colors red *(rosso),* green *(verde),* blue *(blu),* and yellow *(giallo)*—first described by Ewald Hering in his opponent-theory (Chapter 22)—which we now know are transmitted directly to the brain.

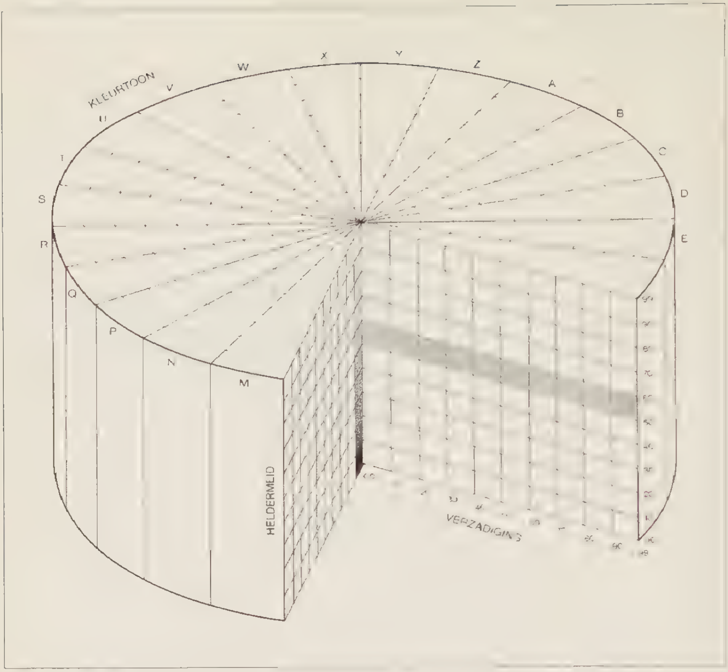
52 ACC SYSTEM

The Acoat Color Codification, a cylindrical color system developed by the paint industry (Sikkens Corporation) to describe color surfaces, originated in Holland in 1978. Theoretically, 2.4 million colors can be calculated with this system, but for practical purposes this number is roughly one million colors for opaque, transparent, glossy, metallic, and other surfaces.

The ACC system uses the techniques of colorimetry to ensure a consistent supply of color batches and color charts, attaining clarity through uniform spacing in the system and economy by avoiding complex conversion procedures between perceived and actual values. In short, it offers color samples at economical prices.

The basis of the ACC system is a color circle comprising 24 chromatic hues *(kleurtoon),* which increase in saturation *(verzadiging)* radially from the center outward, also varying in brightness axially. For each of these parameters 100 gradations from 00 to 99 are provided. The four quadrants of the color circle involve the four basic colors, from red (A), through yellow (G), green (L), blue (T), and back to red. For finer subdivisions, intermediate numbers from 0 to 9 are introduced.

The coordinates of this cylinder are closely related to the CIEL*a*b* system (Chapter 51). Specifically, the ACC system relies on the "perceptual equidistance" of the CIEL*a*b* system. The lines of equal chromatic hue are like beams, jutting out radially from the source of the



coordinates. The construction is open toward black and white, allowing the introduction of new degrees of brightness without a change in the geometry. Black and white thus relinquish their precarious positions at the poles of spheres and cones.

Evidently, the ACC solid also accommodates colors which are brighter than pure white (for example, "day-glow" colors), although in so doing it must forgo very dark shades, which are seldom encountered in practice. The exact coding of colors complies with a six-character triple classification in the sequence chromatic hue, saturation, and brightness. The code C2.55.80 identifies a bright red-orange with low saturation, and G0.55.80 is a yellow color of medium saturation and high brightness. Despite its simple formulae, it is difficult to characterize the Dutch ACC

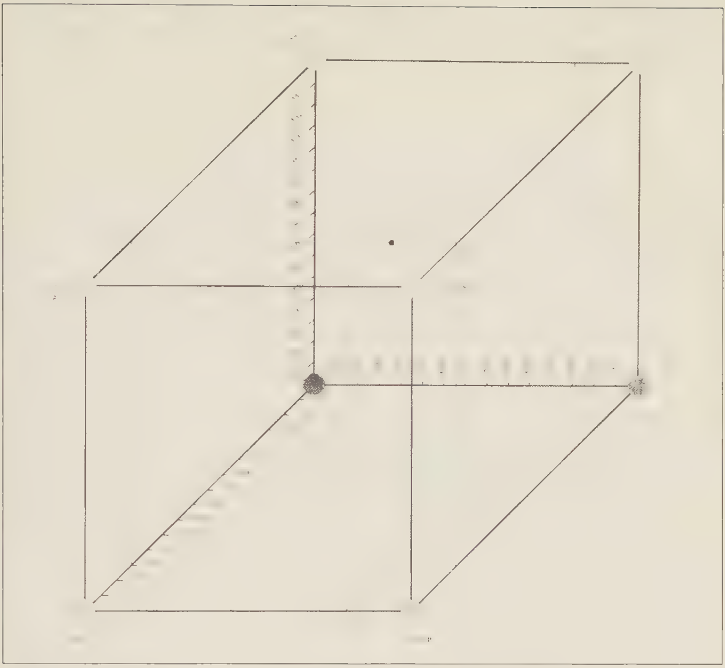
system colorimetrically, to bring it into line with the systems of the German DIN (Chapter 47) or the Swedish NCS (Chapter 50). The European industrial nations have each selected their systems in such a way that other individual national standards are not accounted for. So when a united Europe finally arrives, it may well be a (clashingly) colorful event.

53 RGB SYSTEM

Colors on a television screen are created, as discussed in the text to Chapter 55, by a special form of additive light mixing known as partitive mixing. The surface of the screen is covered by rows of tiny points, approximately 0.2 mm. in diameter, containing phosphorescent materials. Actually, three different types are normally used, selected to transmit red, green, or blue light, after being excited briefly by a beam of electrons sweeping by; that is, after they have absorbed the energy of the electrons, they glow briefly in releasing it. The screen color system presented here is named RGB, after these three colors.

A partitive light mixture is created because the human eye is incapable of perceiving individually the many hundreds of thousands of points—much less the individual triads of red, green, and blue patches into which they are organized—only registering the cumulative effect of many RGB-triads mixed together. Brightness, regulated by the intensity of the electron stream which triggers the phosphorescence, is also only resolved and perceived over a patch of a minimal size.

The colors on the screen, created by partitive mixing of red, green, and blue, are in turn able to produce only a limited number of all the possible colors. The cube construction shown at right has been verified as the most suitable system for representing this particular range of colors. With each edge divided into 16 equal parts, the cube can adequately specify the trichromatic composition of any of



these colors. The eight corners of the cube are occupied by red (R), green (G), and blue (B); the subtractive primary colors magenta (M), yellow (Y), and cyan blue (C); and the achromatic colors black (B) and white (W).

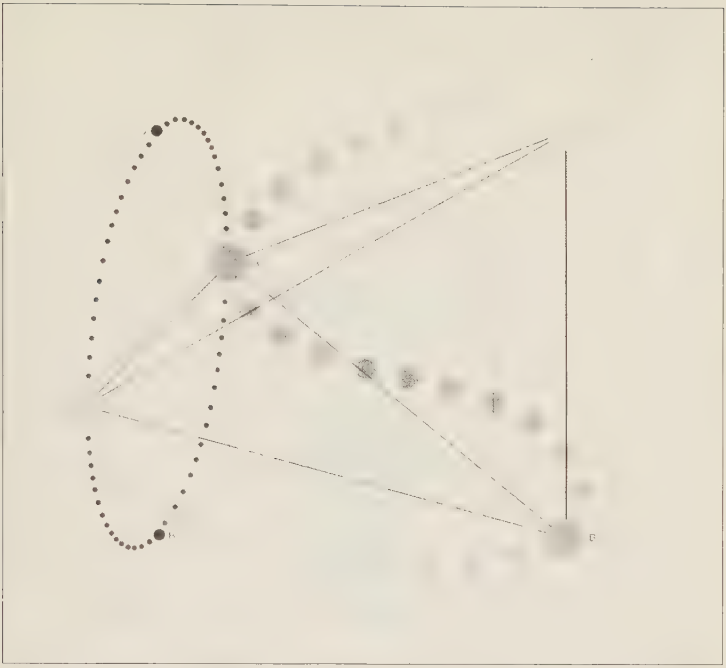
All colors in the RGB system can be concentrated into two subgroups, one centered on white and the other on black. The chromatic form extends from black (0, 0, 0), along the edges of the colors, passing two corners to reach the white apex (15, 15, 15)—the maximum intensity.

54 MICHEL ALBERT VANEL

The "Planetary" color system designed in 1983 by the Frenchman Michel Albert-Vanel is intended to incorporate the effects of the color sensations that we encounter in everyday life. Colors influence each other, and change with their surroundings. The basis of this novel and unorthodox system is the rotating planets, which represent Ewald Hering's four (psychological) primary colors (Chapter 22)—yellow (J for *jaune*), red (R), green (V for *vert*), and blue (B). The secondary colors are represented by moons orbiting them.

Colors are not abstract concepts, but real sensations, usually experienced in groups, not in isolation. We not only associate these groups with each other, but perceive them in their entirety. The planetary system introduces new parameters in order to describe the context in which a color exists. For each color, contrast and material join the usual trio of hue, brightness, and saturation. Contrast unites three new scales describing mixtures or groups of colors. One scale considers hue, as extending from monochromatic (without contrast) to polychromatic (full contrast) colors. The other two scales, involving brightness and saturation, also range from plain to sophisticated colors. The material brings three additional scales into the system, ranging from active (light) to passive (pigments), with the latter extending from transparent to opaque, and from mat to glossy.

A color solid may be constructed by selecting any three scales from this assortment of planetary scales. The system



as a whole can be used, for example, to locate the colors of complex impressionistic pictures, since an almost infinite number of color combinations can be defined by it. Despite this huge number, the everyday sensation of color still centers on a few main color groups, and can thus be represented by planets, orbited by numerous small moons. This is a multidimensional color space.

55 HLS SYSTEM

The letters H, L, and S stand for the classic color variables hue, luminance, and saturation. Intensity (I), often used in place of luminance, would serve equally well here, to create an HIS system. Either way, the system makes it possible to apply A. H. Munsell's system (Chapter 29) to the colors created on television screens by the process of phosphorescence. This term comes from the Greek *phosphoros* meaning "morning star" or "Venus." It could also be translated literally as "carrier of light." The light effect known as phosphorescence occurs when energy delivered in the form of an electron beam is captured by substances on the screen (molecules) and then released in the form of light.

The colored picture on a television screen is actually produced by three different light-absorbing and light-carrying molecules concentrated in triple rows of tiny patches each approximately 0.2 mm. in diameter. When they glow, a particular type of additive light mixing—a so-called partitive mixture—is made, using the three colors red, green, and blue (RGB). This will be explained when we examine the associated RGB system (Chapter 56).

In the HLS system, color hue is specified by an angle which varies from 0 to 360°. Intensity and saturation are measured on a scale of 100 units. Intensity is read off along the axial line between the black and white extremes, and saturation along the radial lines running from gray to full color.

Of course, the problem of mediation between purely numerical (metric) and chromatic (psychological) scales is still present in the HLS system.

56

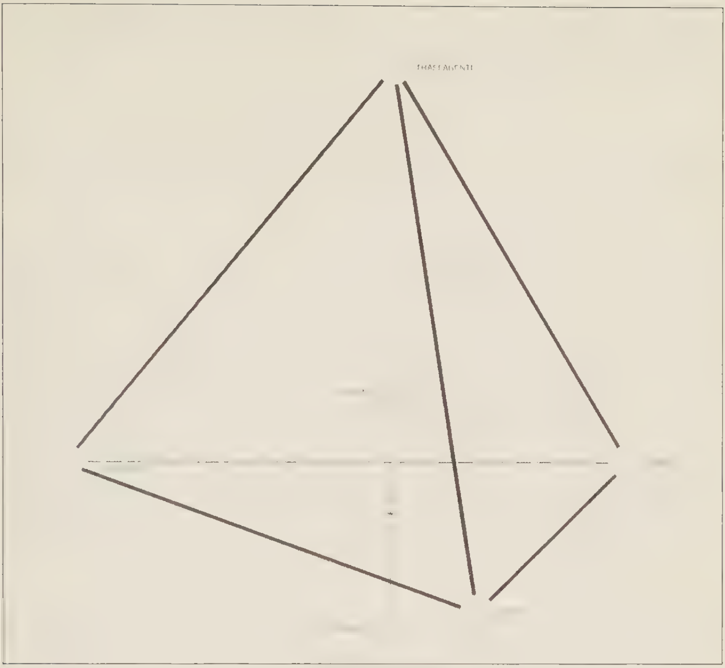
CMN SYSTEM

Colors can change—becoming transformed into other colors, growing brighter or duller, or moving closer to white *(bianco)* or black *(nero).* They can also become more transparent or reflective, thus tending toward "trasparenza" (T) or "specularita" (S). The task set for the Italian CMN-86 color system, dating from 1986, was to record visibly the ways and means by which colors (C) appear, change, and disappear.

The basis for the construction was a tetrahedron, already familiar to us from the geometry of Plato's ideas on color. So we have now come full circle in our selection of color systems. The single tetrahedron can be combined with others, to provide a complete range of spatial models, express the origins of all colors, and reflect other aims of the observer. Although transparency and reflection arise from illuminated objects, colors themselves will always be contributed by the viewer.

With this system, an attempt has been made to give substance to that distant and rather obscure word "colori," the etymological root of which means something "disguised and revealed." Something is extracted from white light, enabling us to see more clearly the object it falls on. To make our world more accessible, we ourselves construct a reality filled with color.

And ultimately, we create a profusion of color systems in order to gain more direct access to the world of colors. We arrange colors into systems so that we can understand their



mixtures, master their diversity, illustrate their dimensions, understand the sensations they induce, or classify their differences. While many principles of order are possible, they are all part of one single ongoing history—but unlike history, which remains open, the systems themselves, once completed, must remain closed.

GLOSSARY OF TERMS

Achromatic colors: black, gray, and white.

Achromatic point: in the CIE diagram the point that represents white, and where the contributions of all the spectral colors possess equal energy. This point, also known as the "mean valency point," is indicated as "E" in the CIE diagram. Any two colors on the CIE diagram's spectral line are complementary if the straight line connecting them runs through this "white point."

Additive color mixture: the mixing of light of varying colors using projectors equipped with suitable filters. Their light is combined on a projection screen. With an additive color mixture, the chromatic colors will combine to form white.

Basic colors: normally implies red, yellow, green, and blue. The terms "primary" and "proto-color" are also frequently used. Writers on color often define their own proto-colors, and painters tend to think about the basic, primary, and proto-colors in a different way than do physicists and chemists.

Brightness: one of the three reference values—the others being hue and saturation—which together determine a color. Brightness is based upon an addition of either white or black, with the colors obtained becoming correspondingly lighter or darker.

Brilliance: the luminance of a color. Dependent on the surface characteristics of the colored object.

Chromatic colors: all the colors that remain after excluding the achromatic colors (black, gray, and white).

Chromaticity: another term for the degree of saturation of a color.

CIE: the abbreviation for the Commission Internationale de l'Eclairage (International Illumination Commission), which in 1931 presented its CIE diagram. This is known in professional circles as the Standard Valency Chart.

Cold colors: generally blue, blue-green, and violet.

Colorimetry: another word for color measurement.

Color diagram: a curve that incorporates all visible colors and elucidates some of the relationships existing between them (for example, the result of a mixture). The most familiar color diagram is the CIE diagram dating from 1931. In this tongue-shaped curve, the curved line on which the spectral colors lie (the spectral line) is closed off by the straight line of purple.

Color circle: the arrangement of spectral colors to form a closed circle, with the opposite ends of the spectrum being linked by purple.

Color constancy: the actual colors of objects depend not only on the objects themselves and the light they reflect,

but also on the nature of the light which falls on them. However, to the brain a white sheet of paper appears white both at noon and in the evening, even though the nature of the light falling on it changes radically during this time, shifting from an optimum of blue toward red. From an evolutionary point of view, color constancy is one of the most important visual functions of the brain.

Color coordinates: the three coordinates of a color space, namely hue, saturation, and brightness.

Color measurement: the attempt to measure a subject's perception of color objectively.

Color mixing: there are two ways of mixing colors; these have only been precisely defined since the 19th century. In the case of additive color mixing, light rays with different (spectral) compositions meet, and a new color arises as a result of their addition; only this new color is now seen. A special type of additive mixing occurs when individual points of color—on television screens or in paintings—are sufficiently small and spaced closely enough that the observer does not see them individually, thus only perceiving their effect as a group. With subtractive mixing, on the other hand, if a portion of a given light wave is removed (subtracted), its color will change. This can occur through reflection from a colored bottle, or through absorption by a filter, for example. If transparent layers of color are placed one on top of the other, or color dyes or pigments are applied thinly or mixed together, a new color will arise as a result of subtractive

color mixing. The rules applying to subtractive mixing are more complicated than for additive mixing.

Color perception: the stimulation of perception by a color.

Color perception parameter: the changing factors that influence how a color is perceived.

Color quality: the degree of a color's chroma (red, yellow, green, blue). In other words, the extent of its saturation or color hue.

Color scale: the range of colors possessed by an organism such as a butterfly, or created by a designer, for example.

Color solid: a three-dimensional arrangement of colors, usually based on a color circle. Color saturation increases from the center toward the periphery, and brightness changes vertical to the plane of the circle, upward toward white and downward toward black.

Color space: the three-dimensional portrayal of colors which arises from the fact that each color can be determined by three factors (hue, saturation, and brightness).

Color system: the attempt to organize the diversity of colors into a closed system with a view to understanding them. Color systems are often conceived as geometrical color bodies (double cones, for example). From the technical point of view, color systems are methods of characterizing and ordering some or all of the colors using specified material standards.

Color theory: an attempt to comprehend the relationship and significance of colors. Goethe's theory is the most widely known.

Color tint or shade: a fine difference in color hue, lighter in the case of a tint, and darker in the case of a shade.

Color valency: the three color values—hue, brightness, and saturation—with which a color mixture can be described.

Color value: the extent to which a particular primary color is involved in an additive mixture.

Complementary colors: colors which when combined result in white in additive mixtures and black in subtractive mixtures. In color circles the complementary colors are usually located opposite one another. Complementary colors can be very exactly determined, for example in the CIE diagram, by the line running through the achromatic point (white point). The complementary color to green, for example, is a reddish purple.

Equidistance: the objective of a color system is often the ordering of colors so that equal differences in our perception of color correspond to equal distances between the colors within the system. The question then is whether the perceived equidistance has been accurately reflected in the system.

Four-color theory: first put forward by psychologists, the idea that yellow is one of the fundamentally perceived

colors along with red, green, and blue. The biological basis and confirmation of the four-color theory lies in the activity of nerve cells which direct the information about light entering the eye to visual centers within the brain.

Full color: colors with no addition of black or white.

Gray value: states the gray content of a color (brightness).

Hue: the chromatic colors differ from the achromatic colors in that a color hue (brilliance, quality, saturation) can be perceived in them. The achromatic colors are sometimes called "hue-free" colors. Color hue can be present to a varying degree, and the associated colors then are—to use the usual term—of varying saturation, and therefore differ from the achromatic colors to a varying degree. Colors of the same hue all contain portions of only one chromatic color, and differ solely in their chroma (saturation) and brightness. These gradations are called "hues," "tints," or "shades." The human eye can probably distinguish between several million hues, tints, or shades (although it can only differentiate between 300 chromatic colors and about 150 gray tones).

Naming of colors: a system of specifying colors using a finite number of words to denote a continuum of colors.

Natural colors: colors created using natural pigments, such as oxides of iron or vegetable dyes.

Opponent cells: nerve cells which are responsible for the perception of blue-yellow or red-green. These cells

become active when the appropriate mixture of the complementary colors (see above) falls on the correct positions on the retina.

Opponent theory: the color theory based on the observation that a reddish yellow and a greenish blue indeed exist, but not a greenish red or a yellowish blue. The idea relates to the fact that opposing colors (complementary colors) are specially registered by separate channels and are not subject to mixing. The existence of opponent cells within the brain confirms the opponent theory.

Optimal colors: theoretical colors for which a wavelength is either 100% present, or not at all.

Pigment: a molecule which can absorb light of a certain wavelength (energy).

Polarity: the significance of some colors as understood through the principle of opposites, first described by Goethe using the term "polarity." While yellow represents warmth, closeness, and strength, blue stands for cold, distance, and weakness.

Primary colors: colors used by artists or scientists as the basis of mixtures to obtain other colors (secondary or tertiary colors). Primary colors cannot be reduced further and are the basis of all color systems. Each system starts out with its own primary colors.

Prism: a glass body with triangularly arranged surfaces which can separate sunlight into its spectral colors.

Prismatic colors: another term for spectral colors.

Proto-colors: generally blue, green, yellow, and red (and often including the achromatic colors black and white).

Pure colors: colors which contain no other color. In the case of light, these are colors which are determined by one wavelength only.

Receptor: a molecule which can receive and absorb something, for example light.

Relative brightness value: a unit of measurement for the brightness of a color in the CIE system.

Saturation: the saturation (also termed "chroma") of a color denotes the extent to which the associated wavelength is dominant. If the dominating wavelength is diluted by white light, the saturation of a color will be reduced. A chromatic color can become less colored through graying and appear subdued. It can be brightened through the addition of white, or made darker by adding black. It will then indeed appear to possess varying degrees of brightness, but will maintain its level of chroma—expressed technically, saturation will not have changed. The rather unfortunate word "saturation" comes from chemistry. If a dye is introduced into a liquid (solvent), the resultant mixture will change its color as more dye is added. This process reaches its physical/chemical limit when no more dye can go into the mixture, and the solution is said to be saturated. The saturation of the color solution will not increase further.

Saturation ("chroma") as a perception of color signifies the extent to which a color deviates from its achromatic extremes.

Secondary colors: the colors in a color system which arise through mixing the primary colors.

Simultaneous contrast: if a given color is observed simultaneously in varied colored environments, it will often look different. When seen against a magenta-like background, a red will appear more orange than the same red seen in front of a yellow-red background. This varying perception of one and the same color is known as simultaneous contrast.

Spectral colors: the colors which become visible when sunlight is allowed to pass through a prism.

Spectrum: neutral (white) light is composed of radiation of all the wavelengths between 380 nm. and 760 nm. If a white ray of light passes through a prism, its components will be deflected to varying degrees by the process of diffraction. A band of light will become visible, possessing the colors of the rainbow and known as the spectrum. The spectrum begins with red at the long-wave end, changes through yellow and green at its medium-wave center, ending with violet at the short-wave end. This physical spectrum continues at its infrared and ultraviolet ends, although the radiation there is invisible to us.

Standard light source: a light source with specified radiation characteristics used in the measurement of a color.

Subtractive color mixing: when light is passed consecutively through colored filters; with paints (or other non-self-illuminated bodies) this will be the result of simple mixing. Subtractive mixing of chromatic colors can result in black.

Successive contrast: the afterimage of a succession of optical impressions will appear as the reverse image of the fixed color. This afterimage will therefore show the complementary color, and successive contrast can thus be used to determine this color. If, for example, we first observe blue rings on a red background, and then look at a white background, we will see a complementary afterimage of the previously observed arrangement of colors, namely yellow rings on a greenish background.

Tertiary colors: the colors of a system which arise through mixing the secondary colors.

Trichromatic system: another term for three-color (trichromatic) theory.

Trichromatic theory: the idea, mainly put forward by physicists, that all colors can be created by mixing three basic colors: red, green and blue in most cases. The trichromatic (three-color) theory has its foundation in biology, and it is proven by the discovery of the three color receptors in the cones which form a fundamental component of the human retina.

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